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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

CARRIER AIR WING TACTICS INCORPORATING THE NAVY UNMANNED COMBAT AIR SYSTEM (NUCAS)

by

Travis J. Gill

March 2010

Thesis Advisor:	Susan M. Sanchez
Second Reader:	Douglas E. Otte

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REPORT DOCUMENTATION PAGE		Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** March 2010	**1. AGENCY USE ONLY** *(Leave blank)*

4. TITLE AND SUBTITLE
Carrier Air Wing Tactics Incorporating Navy Unmanned Combat Air System (NUCAS)

5. FUNDING NUMBERS

6. AUTHOR(S) Travis J. Gill

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Air Warfare Center Weapons Division
Code 750000D, 1 Administration Circle
China Lake, CA 93555-6001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

The United States Navy has established a Program Office for Acquisition, PMA-268, to develop the Navy Unmanned Combat Air System (NUCAS). The NUCAS will be a fighter-sized aircraft capable of a variety of missions including deep-strike, Intelligence Surveillance and Reconnaissance (ISR), Time Sensitive Targeting (TST) and Air-to-Air Refueling (AAR).

The NUCAS will offer new capabilities to the operability of a Carrier Air Wing (CAW). Potential benefits include improvements in combat sortie completion rate for manned aircraft such as the F/A-18 Super Hornet and the F-35C Lighting II Joint Strike Fighter (JSF).

In this thesis, we evaluate a strike scenario that focuses on the coordination of the NUCAS, the F/A-18 Super Hornet, and the F-35C Lightning II. We construct a simulation model of the scenario, and use a designed experiment to run 12,000 simulated coordinated strike events. We then use a variety of statistical and graphical tools to evaluate the result in order to determine the quantity of aircraft required for mission success, and operational factors necessary to limit friendly aircraft losses.

The results indicate that a division of four NUCAS aircraft is advantageous, in terms of achieved high target casualty rates and high blue survivability rates. The results also highlight the necessity of stealth technology requirements in future aircraft development.

14. SUBJECT TERMS
Unmanned Combat Air System (UCAS), Carrier Air Wing (CAW), Strike Aircraft, X-47B, Defensive Counter Air (DCA), Aerial Refueling (AF) Remotely Manned Vehicles, Data Farming, MANA, Simulation and Efficient Design Center (SEED)

15. NUMBER OF PAGES
77

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**17. SECURITY CLASSIFICATION OF REPORT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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CARRIER AIR WING TACTICS INCORPORATING THE NAVY UNMANNED COMBAT AIR SYSTEM (NUCAS)

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
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THESIS DISCLAIMER

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEW	Airborne Early Warning
AF	Aerial Refueling
AMRAAM	Advanced Medium-Range Air-to-Air Missile
CAS	Close Air Support
CAG	Carrier Air Group
CAW	Carrier Air Wing
CSG	Carrier Strike Group
DCA	Defensive Counter Air
DTA	Defense Technology Agency
EA	Electronic Attack
CGI	Ground Controlled Interception
IDFW	International Data Farming Workshop
ISR	Intelligence Surveillance and Reconnaissance
JSF	Joint Strike Fighter
JDAM	Joint Direct Attack Munitions
MANA	Map Aware Non-uniform Automata
MOE	Measures of Effectiveness
NAVAIR	Naval Air Systems Command
NOLH	Nearly Orthogonal Latin Hypercube
NPS	Naval Postgraduate School
NUCAS	Navy Unmanned Combat Air System
OCA	Offensive Counter Air
OEF	Operation Enduring Freedom
P_d	Probability of Detection
P_k	Probability of Kill
R^2	R Squared
RCS	RADAR Cross Section
SAM	Surface to Air Missile

SD	Standard Deviation
SEED	Simulation Experiments and Efficient Designs
SIGINT	Signals Intelligence
TACAIR	Tactical Aircraft
TST	Time Sensitive Targeting
UAV	Un-manned Air Vehicle
WEZ	Weapons Engagement Zone
XML	eXtensible Markup Language

ACKNOWLEDGMENTS

First, I would like to thank my Father in Heaven who has blessed me with an incredible career in naval aviation. He has also blessed me with a wonderful and supportive wife, Chantil, and two beautiful children: Sierra, a confident determined daughter, and Aaron, a consistently cheerful son. I am grateful for their continued support on this journey through life.

Thank you to Mr. Ken Amster of NAVAIR China Lake, who continues to provide NPS with aviation-themed thesis ideas.

A sincere thank you to my advisor, Dr. Susan Sanchez, who allowed me to combine my professional knowledge in naval aviation with her invaluable simulation, design of experiments, and data analysis experience to produce a quality thesis. Dr. Susan Sanchez also invited me to attend the 19th International Data Farming Workshop in Auckland, New Zealand, where I gained valuable experience working with the developers and programmers of MANA and the Defense Technology Agency (DTA).

My thanks to Mark Anderson of New Zealand's DTA who dedicated hours to help in the design of my MANA simulation. Ka kite ano!

I would also like to earnestly thank Research Associate Mary McDonald who assisted significantly to designing and improving my MANA simulations and running the design of experiments.

CAPT Doug "Otter" Otte, thank you for being my second reader for my thesis. Your insight to naval aviation with a "big picture" approach to operations analysis was key in directing the process.

Finally, I want to thank my dear friend, Kenneth Byers, who dedicated selflessly to helping me get through the difficult portions of this very challenging degree. You made a difference!

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EXECUTIVE SUMMARY

The Navy Unmanned Combat Air System (NUCAS) will be a fighter-sized aircraft capable of a variety of missions. The NUCAS will offer significant additions to the operability of a Carrier Air Wing (CAW) with improvements in combat effectiveness and aircrew survivability. With a projected combat radius of 1,500 to 2,100 nautical miles, the NUCAS should be able to strike targets deep within enemy territory. When deployed as part of a CAW, the NUCAS must safely and effectively be integrated with the over 70 other jet and rotary-wing aircraft currently operating on a modern naval aircraft carrier.

In this thesis, we examine two questions:

- What combination of manned and unmanned aircraft provides the best mission success rate?
- What operational factors allow the NUCAS to complete its mission with limited loss rate to manned and unmanned aircraft?

We design a coordinated strike scenario using an agent based combat-modeling program called Map Aware Non-uniform Automata (MANA) to test the interaction of the NUCAS among current and future manned aircraft such as the F/A-18 Super Hornet and the F-35C Lightening II Joint Strike Fighter (JSF). This coordinated strike scenario is created to stress the capabilities of each aircraft in order to gain some insight into the factors that provide for mission success and limited friendly aircraft losses. A variety of unit factors are included in the simulation, including aircraft starting locations, quantities, stealth, various sensor characteristics, and various weapons characteristics. By utilizing design of experiment techniques, we adjust these unit factors for each of the friendly and enemy agents, thus creating 240 different numbers of combinations that we evaluate and analyze.

Our analysis of the 12,000 simulated results provides some insights about mission success and friendly survivability:

- NUCAS aircraft should be operated in a group of at least three to four aircraft.
- F-35C aircraft should operate in a group of at least four aircraft when used for OCA missions against a large number of enemy aircraft.
- Stealth is an important factor for both successful target destruction and blue survivability.
- Weapons P_{hit} is a major factor in target destruction and blue survivability.

Our approach shows how simulation, data farming techniques, and data analysis can be used to explore CAW operations. The results of our analysis can be used to assist the U.S. Navy and Naval Air System Command (NAVAIR) as they continue to develop tactics for the future of CAW and the NUCAS. By modifying the simulation model, adding exploring models of additional missions, or using this approach on other models of NUCAS capabilities and CAW operations, additional insights to the capabilities of the NUCAS can be addressed as continued development of the NUCAS program continues.

I. INTRODUCTION

> Aircraft carriers are one of America's key power-projection systems. To ensure their continued operational effectiveness and survivability in the future security environment, they need to be equipped with new air platforms with greater range, greater persistence, and improved stealth. (Ehrhard and Work, 2007)

A. OVERVIEW

Naval aviation has changed dramatically over the past decade. The catalyst of this change was the collapse of the Soviet Union and the rise of terrorist cells capable of coordinating the horrific attacks of September 11, 2001. There has been a shift from larger, long-ranged, single-role aircraft such as the F-14B Tomcat and A-6 Intruder, to the smaller, shorter-range, multirole F/A-18C Hornet and the F/A-18E/F Super Hornet. The F/A-18 has been the "tip-of-the-spear" aircraft since 1983 and has proven itself to be very capable in carrier and combat operations. In Operation Desert Storm, a section of F/A-18 pilots were credited with two MiG-21 kills followed by the successful bombing of ground targets on the same mission. Ever since its introduction, the F/A-18 has continued to break records for availability, reliability, and maintainability (Federation of American Scientists, 2010). Within the next few years, the F/A-18 will replace all but the E-2C Hawkeye Airborne Early Warning (AEW) aircraft, and the MH-60 Seahawk helicopters in a Carrier Air Wing (CAW)

A future aircraft, the F-35C Lightning II Joint Strike Fighter (JSF), is currently in testing and is planned to replace the older F/A-18C. The F-35C brings a decade of advances in sensors and avionics, vastly improved stealth utilizing internal armaments, and the promise of improved maintenance and reliability.

As remarkable as these advances are, both the F/A-18 and the F-35C are surprisingly limited in their combat radius and endurance. The typical carrier air wing of the "Reagan Years" consisted of F-14Bs, A-6s, and other aircraft having combat radii well over 800 nautical miles. In contrast, our current F/A-18 aircraft is limited to roughly 400 nautical miles using a typical combat configuration of air and ground attack

weapons. It is expected that the future's F-35C will only extend combat ranges by another 100 nautical miles (Jane's All the World's Aircraft, 2009).

An example of how combat range affects the Navy's ability to support coalition forces can be seen in air combat operations of Operation Enduring Freedom (OEF). U.S. F/A-18s launch from the aircraft carrier stationed in the North Arabian Sea. They fly north, along the nearly 400-mile airspace corridor over Pakistan, before reaching Southern Afghanistan where they proceed to their first tanker. After tanking, they can expect to report on station and support ground troops for roughly two hours before requiring their second tanking. The F/A-18 aircrew will then spend roughly two more hours on station before having to join a third tanker in order to make the transit south and finally recover on the aircraft carrier. Tanking operations take time and require the aircraft to leave its area of responsibility to proceed to the tanker staging area. This greatly reduced the persistence, i.e., the ability of an aircraft to loiter over the area of concern. There is clearly room for improvement.

B. BACKGROUND AND MOTIVATION

The Navy has committed to developing and acquiring the Navy Unmanned Combat Air System (NUCAS). The NUCAS will be a fighter-sized aircraft capable of a variety of missions, including Deep-strike, Intelligence, Surveillance, and Reconnaissance (ISR), Time-Sensitive Targeting (TST), and Air Refueling (AF).

The NUCAS will significantly advance carrier aviation where manned and unmanned aircraft will work in partnership within a single environment. The Navy anticipates that the NUCAS will offer significant additions to the operability of a Carrier Air Wing with improvements in combat effectiveness and aircrew survivability.

The NUCAS has the potential to restore the U.S. Navy's deep strike capabilities, and to extend the combat radius required for effective combat operations. With a projected combat radius of 1,500 to 2,100 nautical miles, the NUCAS should be able to strike targets deep within enemy territory. The NUCAS is also being developed with the capability of receiving in-flight aerial refueling, thus extending the NUCAS's range

almost indefinitely. With in-flight refueling, a NUCAS could conceivably stay airborne for hundreds of hours without any of the concerns that have affected manned aircraft, such as pilot fatigue or performance-related blackouts. This not only benefits the Navy's deep-strike capability but also increases the NUCAS's potential loiter time. This suggests that ISR missions could greatly benefit from the nearly unlimited on-station time the NUCAS provides.

The current NUCAS Demonstrator, Northrop Grumman's X-47B, is still in its development phase. The current objectives (Northrop Grumman, 2010) are to: demonstrate the technical feasibility of carrier landings with a tail-less, low observable relevant platform prototype, continue the maturation of relevant carrier landing and integration technologies, and conduct actual NUCAS carrier landings.

The NUCAS must safely and effectively be integrated with the over 70 other jet and rotary-wing aircraft currently operating within the cramped, 4.5 acres of a modern naval aircraft carrier. Once the Navy demonstrates the feasibility of NUCAS carrier landings, continued development will determine missions and tactics that effectively employ the NUCAS within the CAW.

2. NUCAS Missions

The two most obvious missions include Intelligence Surveillance and Reconnaissance (ISR) and Time Sensitive Targeting (TST), due to the requirements for extended range and loiter time offered by the NUCAS. Air-to-ground missions for the NUCAS may include Close Air Support (CAS), long-range strike, and coordinated strike. Future advances may include an air-to-air capability on the NUCAS thus expanding missions to include Offensive Counter Air (OCA), and Defensive Counter Air (DCA).

This thesis focuses on the coordinated strike mission. We choose the coordinated strike scenario because it is the hallmark training scenario for all fixed-wing carrier aviators. The complexities that arise from operating multi-purposed aircraft within the same battle-space can be challenging. Each aircraft has its area of responsibility to include:

- Initial air-to-air engagements
- Air-to-air protection for the air-to-ground strike aircraft
- Air-to-ground strike aircraft
- Electronic Attack (EA) aircraft
- Command, Control and Communications (C3) aircraft
- Signal Intelligence (SIGINT) aircraft

In this thesis, we model the first three aspects.

C. RESEARCH QUESTIONS

Thus the objective of this thesis is to demonstrate how the NUCAS can be evaluated through the use of simulation, design of experiments, and data analysis. Specifically, this thesis evaluates a coordinated strike scenario utilizing the NUCAS as an air-to-ground strike aircraft and Offensive Counter Air (OCA) supplied by F/A-18 and F-35C aircraft. Specific questions directing this thesis include:

- What combination of manned and unmanned aircraft provides the best mission success rate?
- What operational factors allow the NUCAS to complete its mission with limited loss rate to manned and unmanned aircraft?

D. BENEFITS OF THE STUDY

The Naval Air System Command (NAVAIR) is responsible for the future capabilities of aircraft and aircraft-related weapons systems. Effectively integrating the NUCAS into the future CAW will require decisions on how many UCAVs should be in an airwing, what functions they should be expected to have, how their presence will change current airwing operations, etc. The findings of this thesis provides preliminary insights to Navy decision-makers that may help them address these issues. This thesis also serves as an example of how simulation experiments and data analysis can be leveraged to investigate CAW operations. A similar approach may be beneficial for

assessing a variety of CAW missions involving NUCAS. As the NUCAS moves beyond its demonstration phase, more detailed models of NUCAS capabilities and CAW operations can be developed.

E. METHODOLOGY

Utilizing analytical techniques developed and implemented at Naval Postgraduate School (NPS), this thesis provides some preliminary guidance about the operational requirements of the NUCAS in a variety of mission areas. Design of experiments techniques and procedures are utilized to vary NUCAS operational parameters. We create scenarios using an agent-based computer simulation modeling platform called Map Aware Non-uniform Automata (MANA). By using MANA, baseline scenarios can be created relatively quickly, and then investigated using an approach known as data farming. In data farming, simulation parameters are varied according to a designed experiment, to create a set of well-chosen variations of the scenario. These variations are simulated multiple times, and the data analyzed to identify those parameters that have the greatest effect on mission success. This helps future developers focus on the parameters that actually make the biggest impact, therefore providing better insights about NUCAS employment and effectiveness.

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II. SIMULATION DEVELOPMENT

A. OVERVIEW

This chapter provides further elaboration on the NUCAS and the simulation model used to test the tactics in which the NUCAS can be expected to operate. The purpose of this thesis is not to recreate every conceivable operational environment in which the NUCAS might be employed, but to look at a coordinated strike scenario simulation. Our scenario is constructed in Map Aware Non-uniform Automata (MANA), an agent-based simulation developed by the Defense Technology Agency (DTA) of New Zealand.

B. MANA SIMULATION

The primary strength of MANA is that it can be utilized effectively to generate simulation experiments in a relatively quick fashion. MANA allows various assumptions and agents characteristics to be parametrically changed and the simulation run again. This facilitates the ability to investigate the impacts of varying several independent factors on mission outcome. MANA is well documented, providing information on MANA's many uses, agent parameters, and capabilities.

MANA was designed by DTA to research the often-random complexities of combat operations. As an agent-based simulation, MANA focuses on individual "agents" that have characteristics that can be adjusted utilizing a wide variety of parameters. Some of the major agent parameters include:

- Type (i.e., enemy, friendly, neutral)
- Quantity
- Speed
- Concealment or stealth
- Weapons

- Sensors
- Communications between agents
- Interaction characteristics between various other agents

MANA is extremely customizable, allowing for a wide variety of problems to be modeled through simulation. Many components, such as sensors and weapons, are fairly detailed and include parameters such as probability of hit and probability of kill for variable ranges. Other aspects, such as fuel usage, are rather simplistic, with only a single fuel-consumption rate for a particular agent.

DTA performs periodic updates to MANA. We use version 5.00, known as MANA V, for this thesis's simulation building process. Figure 1 shows the start-up screen for MANA V.

NEW ZEALAND
MANA V
DTA
DEFENCE TECHNOLOGY AGENCY
Vector-Based Movement
Map Aware Non-uniform Automata
This software has been developed by Gregory McIntosh, David Galligan, Mark Anderson and Michael Lauren for the New Zealand Army and Defence Force.
Terms of use:
This software belongs to the Defence Technology Agency (DTA), New Zealand Defence Force. It is not to be distributed without the permission of DTA. This product is not to be offered for resale.
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Figure 1. Screen Shot of MANA V Startup Screen (From Defense Technology Agency, 2010)

C. MISSION SCENARIO

A Carrier Strike Group (CSG) is operating off the coast of a threatening nation. Intelligence reports that the threatening nation is in the process of resurrecting a ground-based anti-ship missile system near its coast. This missile system has been deemed a threat to region stability.

1. Enemy Forces

Enemy defenses include two squadrons of Chinese-built Chengdu J-10 aircraft. All enemy aircraft operate from a known airfield located on the coast. Intelligence reports that the enemy aircraft have been regularly conducting Combat Air Patrol (CAP) missions along the coast. SIGINT also suggests that the enemy has alert aircraft that can be launched from the airfield on short notice. The enemy has a very robust early warning detection system, providing the capability to classify and target air contacts using Ground Controlled Interception (CGI).

2. Friendly Forces

The CAW consists of three squadrons of TACAIR aircraft: F/A-18F Super Hornets, F-35C Lightning IIs, and the NUCAS strike aircraft. The F/A-18F and F-35C are configured for air-to-air engagements and are primarily responsible for protecting the strike aircraft. The NUCAS is the strike aircraft and is configured with air-to-ground weapons. The NUCAS is the strike aircraft, rather than a manned aircraft because of the significant threat over the enemy target area.

3. Terrain and Scale

The Area of Operations (AOA) is a 500 NM by 500 NM area with the threatening country towards the north and the CSG located in the south. The enemy J-10 CAP aircraft are already on station and will respond immediately to any perceived threat that approaches their coast. The enemy airfield is located to the northeast on the coast and will launch aircraft to intercept an inbound air threat.

4. Mission

The Carrier Air Group (CAG) has been ordered to plan and conduct a coordinated air strike on the threatening county. The primary target is the anti-ship missile system near the coast. The F/A-18F and F-35C aircraft will provide offensive counter air, targeting any enemy aircraft they encounter. The NUCAS will strike the target using GPS-guided bombs. We also assumed that EA, C3, and SIGINT capabilities will be provided by other aircraft, but do not explicitly model these in the simulation. Figure 2 shows the MANA screen shot of the coordinated strike scenario.

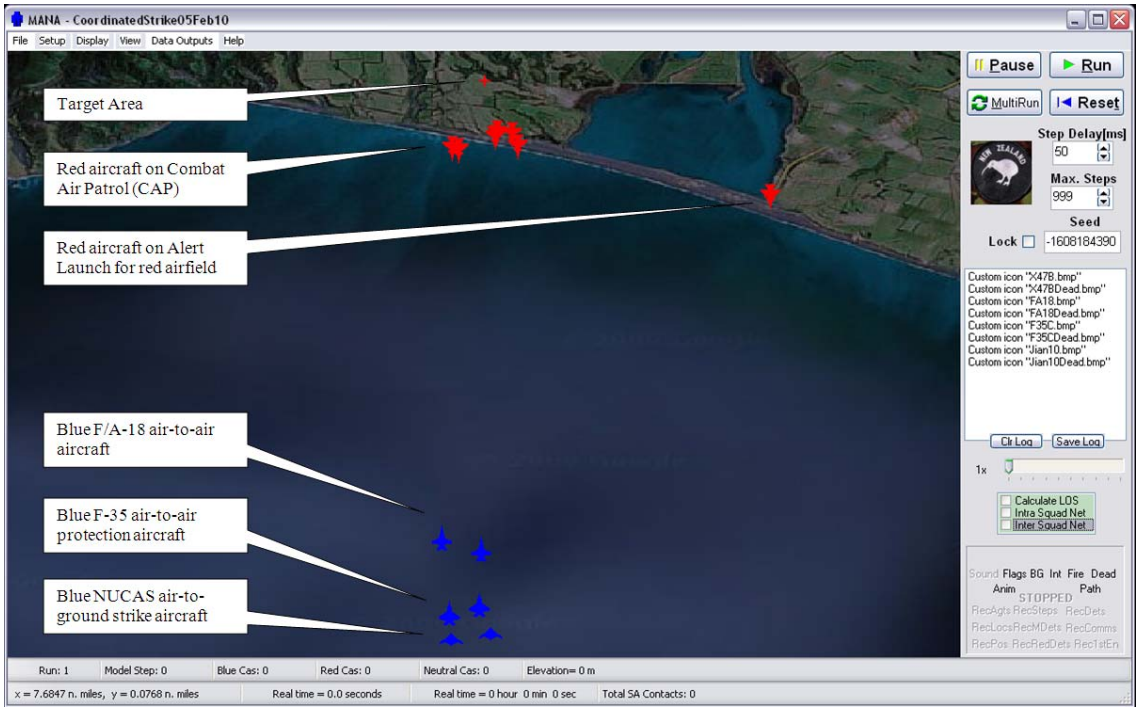

Figure 2. MANA Screen Shot of Coordinated Strike Scenario (After Defense Technology Agency, 2010)

D. SIMULATION MODELING CHARACTERISTICS

This section describes the various characteristics of the MANA simulation model that we use for this thesis.

1. Goals of the Simulation

The NUCAS is still in the development process with limited test flights being scheduled for early 2010. An actual NUCAS carrier landing will not be conducted until late 2010 at the earliest. It is expected that a squadron of NUCAS aircraft will not be established until 2015. Using an actual aircraft in a war game against an enemy threat simply cannot be accomplished, thus the reason for simulation.

The simulation and scenario are created to stress the capabilities of each aircraft in order to gain some insight into the factors that provide for mission success. For this simulation, mission success is measured in the ability of the friendly agents to successfully destroy the target area. Friendly losses are also evaluated because losing 95 percent of your friendly forces to destroy a target is not considered a mission success.

In order to determine mission success, the simulation has a variety of unit factors that include: location, quantity, stealth, various sensor characteristics, and various weapons characteristics. By utilizing design of experiment techniques, we adjust these unit factors for each of the friendly and enemy agents, creating an abundant number of combinations that can be evaluated and analyzed.

2. Time, Scale, and Map

MANA is a time-stepped model that requires pairing between the simulation clock and the actual world event that is being simulated. This simulation uses 30 seconds to represent a single time step. The simulation time typically takes no more than 235 steps, corresponding to just less than two hours of actual time.

MANA refers to the geographical area within the model as the “battlefield”. For this simulation the battlefield is x = 50.0 by y = 50.0 grid which corresponds to 500 by 500 nautical miles of geographical area. Coordinates start in the upper left quadrant of the battlefield and increase until reaching the bottom right quadrant.

MANA has an upper range limit of 100,000 meters, or 62.14 miles. MANA sensor and weapons ranges are a few of the factors that have this limit. Since this thesis required sensor ranges beyond 62.14 miles but not beyond 621.4 miles, we reduced the

battlefield scale by a factor of 10. All simulation distances are reduced by this factor in order to overcome the MANA limitation. Figure 3 shows the battlefield settings menu, where map size and model time step are indicated.

MANA provides a means for maps to be added to the simulation background. A map of the simulation area was obtained from a screen capture of Google Earth, darkened using Adobe Photoshop, and then saved as a .bmp image. The image was then imported into MANA by manually updating the <Battlefield> portion of the code in the eXtensible Markup Language (XML) file. Introducing this map in the background does not impact the agents being simulated or their behavior. The background map is simply used to increase user situational awareness of the simulation area.

Figure 3. Screen Shot of the Battlefield Setting Menu (From Defense Technology Agency, 2010)

3. Enemy Forces

This scenario uses three enemy agents as described in Table 1.

Agent	Icon	Description
CAP J-10		Aircraft already in flight (on patrol) at the start of simulation.
Alert J-10		Aircraft on alert at the airfield for launch as directed (random).
Target Area		The ground-based anti-ship missile site.

Table 1. Enemy Agents Used in MANA Simulation

MANA uses the term “squads” to represent agents. The scenario starts with all squads in position; their start locations are determined by a home position and box size centered on the home location. The CAP J-10s are located at their CAP station, designated in MANA as x = 25 and y = 8. The individual aircraft associated with this squad are randomly populated within a rectangle box of x = 5.0 and y = 2.5. As previously mentioned, all measurements are reduced by a factor of 10; therefore this corresponds to a real-world area of 50 by 25 nautical miles.

The Alert J-10s are located at their associated airfield located in MANA as x = 40, y = 12. Once the simulation starts, a countdown timer of 3600 seconds (1 hour) is activated. All Alert J-10s will launch at random intervals until the 3600 seconds is reached.

In MANA, “Squad Personalities” determine how squads react with other agent squads. Various levels of personalities can be adjusted from -100 to +100, thus allowing for a wide variety of squad characteristics and behaviors. For example, a squad assigned a -100 to “Enemy Threat” would respond by moving away from that threat. Conversely, a squad assigned a +100 would move towards that threat. Both the CAP J-10s and Alert J-10s are set to pursue all threat aircraft with +100. If no threat aircraft are within sensor range, the aircraft have a secondary personality, of +15, to move towards their waypoint located at x = 25, y = 15.

Another factor of a squad is what MANA refers to as "concealment." Concealment affects the probability that a squad can be seen in a given time step. For example, a squad having a concealment value of 1.00 is completely invisible. Conversely, a squad having a value of 0.0 is completely visible. For aircraft like the J-10, this concealment value can be associated with stealth. Both the J-10 squads are given an adjusted concealment level from 25 to 90 percent of the base concealment. This corresponds to a real-world RADAR Cross Section (RCS) of 0.75 to 0.1 m^2 RCS (Grining, 2000).

Sensor range can also be adjusted. Both J-10 sensor classification ranges are set to the maximum limit of 100,000 meters (621.4 miles). This maximum range is chosen to simulate the added advantage the enemy country has when classifying air targets as threats. We assume that the enemy has established a no-fly exclusion zone, so any aircraft approaching their coast will be declared hostile and fired upon.

MANA also allows for a wide variety of weapons to be employed for each squad. The J-10 employs two primary air-to-air missiles: The PL-12, medium-range, active-radar missile and the PL-8, short-range, infrared seeking missile. The PL-12 and PL-8 quantity, range, and probability of Kill (P_k) can be adjusted in MANA's "Weapons" tab of the "Squad Properties" menu. Using design of experiments, we adjust each of these factors during the simulation. Table 2 describes the factors, along with their minimum and maximum values.

The "Target Area" is specified as a squad as well. However, the target area is very different from the other squads since it does not have a movement, personalities, weapons, or sensors. The Target Area has only two parameters associated with it. The first is a threat level that is only targeted by the NUCAS. The second parameter is a requirement that two NUCAS hits are necessary in order for the target to be destroyed. These two parameters are necessary in order to keep air-to-air units from attacking the Target Area, and to create a more realistic scenario in which two bomb hits are required for successful destruction.

Agent	Factor	Min	Max	Explanation (Units)	Notes
J-10 CAP	Number of Agents	1	20	Number of aircraft	
	Movement Speed	25	80	Speed (knots x 10)	
	Personal Concealment	25	90	Probability of detection (%)	0.75─0.1 m2 RCS
	PL-12 Weapon Shots/Ammo	1	6	Number of weapons	
	PL-12 Weapon Range	5632	8046	Weapons range (meters x 10)	35─50 miles
	PL-12 Weapon Hit Rate per Discharge	0	1.00	Probability of hitting target (%)	
	PL-8 Weapon Shots/Ammo	2	4	Number of weapons	
	PL-8 Weapon Range	322	1609	Weapons range (meters x 10)	2─10 miles
	PL-8 Weapon Hit Rate per Discharge	0	1.00	Probability of hitting target (%)	
J-10 Alert	Number of Agents	1	20	Number of aircraft	
	Movement Speed	25	80	Speed (knots x 10)	
	Personal Concealment	25	90	Probability of detection (%)	0.75─0.1 m2 RCS

Table 2. Table of Enemy Factors and Their Associated Min/Max Values

4. Friendly Forces

The scenario uses three main friendly agents, as described in Table 3.

Agent	Icon	Description
NUCAS		Unmanned strike aircraft configured with air-to-ground bombs.
F/A-18F		OCA aircraft configured with air-to-air missiles.
F-35C		OCA aircraft configured with air-to-air missiles.

Table 3. Friendly Agents Used in MANA Simulation

The friendly squads start the simulation on the southern portion of the battlefield. The NUCAS are located the furthest south at the start position of x = 25 and y = 47.5. Since the NUCAS are the only aircraft in the strike package with an air-to-ground

weapon, it is vital that other aircraft protect the NUCAS from any air-to-air threats. These protection aircraft are referred to as Offensive Counter Air (OCA) and they have the responsibility of clearing the airspace of enemy aircraft. The F-35C and F/A-18F are the OCA and will have a start location of x = 25; their y = locations varies between 27.5 to 47.5 placing the OCA aircraft in front of the strike NUCAS.

In addition to the start location, each of the friendly squads also has waypoints which they move towards. The first waypoint is located at x = 25 and y = 3.5 and corresponds to the target location. Once the friendly squads reach the target waypoint, a second waypoint is activated and a return to the final location at x = 25 and y = 47.5 is directed.

The squad personalities for the NUCAS and the other blue aircraft are very different from each other. The NUCAS has two threat levels that it uses to differentiate between the J-10 threat and the Target Area threat. The NUCAS will proceed towards the Target Area with a personality weight of +100 and it will move away from the J-10 threat with a personality weight of -30. The F/A-18 and the F-35C have only one threat, the J-10s, and they will move towards that threat with a personality weight of +100. Also, in order to keep all of the blue squads moving along the flight path, we implemented a personality weight of +30 for proceeding to the specified waypoint.

The MANA concealment factor for the blue squad representation is the same as for the J-10, except the values are higher to represent the smaller RCS values of the stealthy F-35C and NUCAS. Table 4 lists the personal concealment values for each of the friendly aircraft in the simulation model.

Research done on the sensor classification range and aperture provided a wide variety of capabilities. The sensor systems for all of the blue squads are classified, but we obtained reasonable numbers from unclassified sources such as Jane’s Aircraft. The NUCAS sensor systems have not been developed at the time of this thesis so assumptions are necessary. Since the NUCAS is smaller than the F/A-18, we assume that the sensor systems for the NUCAS will have to be small as well, therefore the NUCAS will have a range and aperture arc similar to those of a current F/A-18F aircraft. The F-35 RADAR,

the AN/APG-81, will have substantial higher ranges and capability than the current F/A-18's AN/APG-74 (Northrop Grumman 2010). Table 4 lists sensor classification ranges and aperture arcs for each of the blue squads.

Agent	Factor	Min	Max	Explanation (Units)	Notes
NUCAS	Number of Agents	1	12	Number of aircraft	
	Movement Speed	25	65	Speed (knots x 10)	
	Personal Concealment	98	100	Probability of detection (%)	0.0015─0.0001 m2 RCS
	Sensor Class. Range	9656	16093	Sensor range (meters x 10)	60─100 miles
	Sensor Aperture Arc	40	120	Sensor width (degrees)	
	GBU-31 Weapon Shots/Ammo	1	2	Number of weapons	
	GBU-31 Weapon Range	805	2736	Weapons range (meters x 10)	5─17 miles
	GBU-31 Weapon Hit Rate	0	1.00	Probability of hitting target (%)	
F/A-18F	Number of Agents	1	12	Number of aircraft	
	Home Waypoint Location y:	47.5	27.5	Distance aircraft is in front of NUCAS	0─200 nm
	Personal Concealment	25	90	Probability of detection (%)	0.75─0.1 m2 RCS
	Sensor Class. Range	9656	16093	Sensor range (meters x 10)	60─100 miles
	Sensor Aperture Arc	40	120	Sensor width (degrees)	
	AIM-120 Weapon Shots/Ammo	1	6	Number of weapons	
	AIM-120 Weapon Range	4989	15289	Weapons range (meters x 10)	31─95 miles
	AIM-120 Weapon Hit Rate	0	1.00	Probability of hitting target (%)	
	AIM-9 Weapon Shots/Ammo	2	4	Number of weapons	
	AIM-9 Weapon Range	966	1770	Weapons range (meters x 10)	6─11 miles
	AIM-9 Weapon Hit Rate	0	1.00	Probability of hitting target (%)	
F-35C	Number of Agents	1	12	Number of aircraft	
	Home Waypoint Location y:	47.5	27.5	Distance aircraft is in front of NUCAS	0─200 nm
	Personal Concealment	98	100	Probability of detection (%)	0.005─0.0015 m2 RCS
	Sensor Class. Range	9656	19312	Sensor range (meters x 10)	60─120 miles
	Sensor Aperture Arc	40	180	Sensor width (degrees)	

Table 4. Table of Friendly Factors and Their Associated Min/Max Values

The friendly squad weapons systems are very similar to those of the enemy squads. The F/A-18F and F-35C, configured for air-to-air combat, will carry a combination of AIM-120 AMRAAM and AIM-9 Sidewinder missiles. The AIM-120 is a medium-range, active-RADAR missile. The AIM-9 is a short-range, infrared-seeking missile. The AIM-120 and AIM-9 are broken down into just three factors for each weapon: quantity, range, and probability of hit.

The NUCAS will carry two internal GBU-31 Joint Direct Attack Munitions (JDAM). The JDAM is a 2000 lb GPS guided bomb used for ground targets. The NUCAS will not have air-to-air weapons capabilities. The weapons factors for the F/A-18F, F-35C, and NUCAS are also listed in Table 4.

5. Sources, Abstractions, and Assumptions

It is important that the sources of input data, model abstractions, and assumptions are addressed. Obtaining the source material for effectively simulating the aircraft and weapons systems in MANA took a large percentage of the modeling process time. The sources for the performance characteristics were obtained from a wide variety of unclassified sources, including, Jane's Aircraft, the Federation of American Scientists, Global Security.org, and an assortment of aircraft and weapons defense corporation Web sites.

Air combat is a very physics-based environment with weight, thrust, drag, and lift being common characteristics. Air combat is also a three-dimensional environment where altitude advantages often drive the tactics that are developed. Modern day weapons, including missiles and self-steering bombs, also benefit from being studied in a physics-based, three-dimensional world.

MANA is very limited in its ability to model altitude; therefore, this thesis abstracts all squad aircraft and weapons characteristic by placing them at the same operational altitude. In short, the simulation has abstracted the three-dimensional world of air-combat into a top-down, two-dimensional simulation model.

Sensor and weapons ranges are also very simplified. Each of the squads in this simulation uses a single classification range. This is unlike real-world operations where detection probability tends to decrease with range. The probability of detecting a small RCS contact decreases as the contact gets further from to the detection sensor. Weapons ranges and probability of hit (P_{hit}) are also simulated in this fashion, with only a single range and P_{hit} for each of the weapons parameters. MANA does have the ability to assign ranges with various P_{hit} for those ranges, however, that feature was not utilized for this thesis since the additional detail was not necessary given the simplification of altitude.

Fuel consumption is an abstraction in MANA offering limited application. A single value of fuel consumption per time-step can be assigned; however, combat aircraft do not consume fuel at a constant rate. A multitude of factors such as speed, altitude, and configuration, all provide various factors to the fuel consumption rate. Since the coordinated strike scenario does not challenge the combat radius of the aircraft being simulated, it was decided to eliminate the effects of fuel from the simulation.

Communication between squads is another characteristic that can be defined in MANA. This simulation assumes that all communications are perfect and do not have a limited range.

Failure of equipment and operator error is a characteristic that plagues modern-day aircraft and systems. This simulation assumes that equipment failure does not exist; however, A P_{hit} range from 0.0 to 1.00 is defined for each of the weapons used in the simulation.

6. Summary

"Essentially, all models are wrong, but some are useful", is an oft quoted phrase from the statistician George E. P. Box (DeGroot, 1987). The intent of this thesis is to evaluate the effectiveness of using NUCAS as a force-multiplier in future Carrier Air Wings. Simulation models are a useful way to mitigate the human and financial risk involved in actual air-to-air combat.

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III. EXPERIMENTAL DESIGN

A. INTRODUCTION

Data farming is an approach where multiple variations of a model are generated by varying the input parameters in a well-chosen manner, using experimental design (see Sanchez and Wan, 2009). In this thesis, we utilize data farming techniques to create a large data set by simulating a multitude of factor combinations over a substantial number of iterations. Through data analysis, analysts can better understand how these factors (and interactions among these factors) affect the measures of performance and measures of effectiveness. The analysis may help decision-makers make the kinds of assessments that can ultimately lead to real-world success.

B. FACTORS OF INTEREST

For our simulation experiment, we focus on two types of factors: controllable and uncontrollable. Controllable factors are those that the decision maker has control of in the real world, either through development or employment. These factors might include aircraft speed, weapons quantity, or sensor range. Quite often, the controllable factors are also called the decision variables or decision factors. Uncontrollable factors are those that cannot be controlled in the real world, even though they can be controlled within the simulation. These might include enemy characteristics such as quantity, speed, sensor range, and weapon performance, or might include environmental characteristics such as wind speed and cloud cover. Often these are referred to as the noise variables or uncontrollable variables. The uncontrollable and controllable factors in this thesis are summarized in Chapter II, Table 2 and 4, respectfully. We now discuss them in further detail.

The MANA scenario uses nautical miles for battlefield dimensions and movement speeds, however, parameters like sensor range and weapons range use metric units. In many cases, conversions are necessary in order to successfully implement the data into

MANA. The most common conversion is meters to miles (1 mile = 1,609.344 meters) and meters to nautical miles (1 nautical mile = 1852 meters).

1. Controllable Factors

The following controllable factors are the main factors in the experimental design. For consistency, the labels are the same as those produced in MANA output, and the acronym NUCAS is shortened to UCAS.

a. BlueSpd

Blue speed is the speed, in knots, of the friendly aircraft. Blue speed varies from 250 to 650 knots. Since the scenario requires that the strike package maintain formation, the same speed is used for all friendly aircraft within a particular simulation run. This technique, known as lock-stepping, reduces the number of distinct factors that are varied for the experimental design. As discussed in Chapter II, Blue speed is converted to MANA units by dividing the speed (in knots) by ten. A speed of 500 knots corresponds to a MANA speed of 50.

b. UCASQnty

UCAS quantity is the number of UCAS aircraft. This number varies from 1 to 12. The upper limit of 12 is chosen because current CAW squadron aircraft are limited to roughly 10 to 12 aircraft.

c. UCASStlth

UCAS stealth is the UCAS aircraft concealment in percent. This value varies from 98 to 100. These values correspond to a RCS of 0.0015 to 0.0001 m^2 (Grining, 2000). We used a conversion of $100-(RCS\times 1000)=concealment$. Integer values are required for MANA; therefore, concealment is rounded to the nearest integer value.

d. UCASSnsrRnge

UCAS sensor range is the distance at which the UCAS classifies other squads. This value varies from 60 to 100 nautical miles. These distances are based on a similar radar system used in the F/A-18, the AN/APG-73 (Jane's Avionics, 2010).

e. UCASSnsrApture

UCAS sensor aperture is the sensor arc width. This value varies from 40 to 120 degrees (Jane's Avionics, 2010). Squads that are within the range and aperture of the UCAS sensor will be classified; squads that are outside the range or aperture of the UCAS sensor will not.

f. UCASWpnQnty

UCAS weapons quantity is the number of GBU-31 JDAM weapons that each UCAS carries, and is either 1 or 2. The GBU-31 is a 2,000-pound Mk84 bomb fitted with a GPS-guidance kit (Wikipedia, 2010). The maximum weapons load-out for the UCAS is 4,500 pounds (Northrop Grumman, 2010), thus the reason for the upper limit.

g. UCASWpnRange

GBU31 weapons range is the range of the GBU-31 JDAM. This value varies from 5 to 17 miles (Wikipedia, 2010).

h. GBU31WpnPhit

GBU31 weapon probability of hit (P_{hit}) is the probability that the GBU-31 hits the target. This value varies from 0.0 to 1.00.

i. F18Qnty

F/A-18 quantity is the number of F/A-18E/F Super Hornet aircraft. This number varies from 1 to 12. The upper limit of 12 is chosen because current CAW squadron aircraft are limited to roughly 10 to 12 aircraft.

j. F18Lead

F/A-18 lead is the distance, in nautical miles, that the F/A-18E/F Super Hornet is in front of the strike aircraft. This lead distance is important in that it gives the F/A-18 time to detect and destroy a threat before the threat targets the strike aircraft. This distance varies from 0 to 200 nautical miles. F/A-18 lead distance is converted to a y-coordinate start location (y = 27.5 to 47.5) when inputted into the MANA model.

k. F18Stlth

F/A-18 stealth is aircraft concealment in percent. This value varies from 25 to 90. These values correspond to a RCS of 0.075 to 0.01 m^2 (Grining, 2000). A conversion of $100 - (RCS \times 1000) = concealment$ is used.

l. F18SnsrRnge

F/A-18 sensor range is the distance at which the F/A-18E/F Super Hornet classifies other squads. This value varies from 60 to 100 nautical miles. These distances are based on the AN/APG-73 RADAR characteristics (Jane's Avionics, 2010).

m. F18SnsrApture

F/A-18 sensor aperture is the sensor arc width. This value varies from 40 to 120 degrees. Squads that are within the range and aperture of the F/A-18 sensor will be classified; squads that are outside the range or aperture of the F/A-18 sensor will not.

n. AIM120WpnQnty

AIM-120 weapons quantity is the number of AIM-120 AMRAAM missile carried by either the F/A-18 or the F-35C. AIM-120 weapons quantity varies from 1 to 6. This factor is lock-stepped, ensuring that every F/A-18 and F-35Cs will carry the same quantity of AIM-120 missiles.

o. AIM120WpnRange

AIM-120 weapons range is the range of the AIM-120 AMRAAM missile carried by either the F/A-18 or the F-35C. This value varies from 31 to 95 nautical miles (Jane's Air-Launched Weapons, 2010). This factor is lock-stepped between the F/A-18s and F-35C.

p. AIM120WpnPhit

AIM-120 weapon probability of hit (P_{hit}) is the probability that the AIM-120 AMRAAM missile hits the target. This value varies from 0.0 to 1.00.

q. AIM9WpnQnty

AIM-9 weapons quantity is the number of AIM-9 Sidewinder missile carried by either the F/A-18 or the F-35C. AIM-9 weapons quantity varies from 2 to 4. This factor is lock-stepped, therefore, every F/A-18 and F-35C carries the same quantity of AIM-9 missiles.

r. AIM9WpnRange

AIM-9 weapons range is the range of the AIM-9 Sidewinder missiles carried by either the F/A-18 or the F-35C. This value varies from 6 to 11 nautical miles (Jane's Air-Launched Weapons, 2009). This factor is lock-stepped between the F/A-18s and F-35C.

s. AIM9WpnPhit

AIM-120 weapon probability of hit (P_{hit}) is the probability that the AIM-120 AMRAAM missile hits the target. This value varies from 0.0 to 1.00.

t. F35Qnty

F-35 quantity is the number of F-35C JSF aircraft. This number varies from 1 to 12. The upper limit of 12 is chosen because current CAW squadron aircraft are limited to roughly 10 to 12 aircraft.

u. F35Lead

F-35 lead distance is the distance, in nautical miles, that the F-35C JSF is in front of the strike aircraft. This lead distance is important in that it gives the JSF time to detect and destroy a threat before the threat targets the strike aircraft. This distance varies from 0 to 200 nautical miles. F-35 lead distance is converted to a y-coordinate (y = 27.5 to 47.5) start location when inputted into the MANA model.

v. F35Stlth

F-35 stealth is the aircraft concealment in percent. This value varies from 98 to 100. These values correspond to a RCS from 0.005 to 0.0015 m^2 (Grining, 2000). A conversion of $100 - (RCS \times 1000) = concealment$ is used. Integer values are required for MANA, therefore concealment is rounded to the nearest integer value.

w. F35SnsrRng

F-35 sensor range is the distance at which the F-35C JSF classifies other squads. This value varies from 60 to 120 nautical miles. These distances are based on the AN/APG-81 RADAR characteristics (Northrop Grumman, 2010).

x. F35SnsrApture

F-35 sensor aperture is the sensor arc width. This value varies from 40 to 180 degrees (Northrop Grumman, 2010). Squads that are within the range and aperture of the F-35 sensor will be classified; squads that are outside the range or aperture of the F-35 sensor will not.

2. Uncontrollable Factors

The following uncontrollable factors were chosen for the experimental design. For consistency, the labels are the same as those in MANA output.

a. J10CapQty

J-10 CAP quantity is the number of J-10 aircraft that are on CAP station. This number varies from 1 to 20. The upper limit of 20 is chosen because modern day aircraft are rarely deployed in groups larger than 12 to 15 aircraft.

b. J10CapSpd

J-10 CAP speed is the speed, in knots, of the J-10 aircraft. J-10 CAP speed varies from 250 to 800 knots (Jane's All the World's Aircraft, 2010). J-10 CAP speed is converted to MANA units by dividing the speed (in knots) by ten.

c. J10CapStlth

J-10 CAP stealth is the aircraft concealment in percent. This value varies from 25 to 90. Values used are similar to the F/A-18 Super Hornet. These values correspond to a RCS of 0.075 to 0.01 m^2 (Grining, 2000). A conversion of $100 - (RCS \times 1000) = concealment$ is used.

d. PL12Ammo

PL-12 weapons quantity is the number of PL-12 active-RADAR missiles carried by the J-10. PL-12 weapons quantity varies from 1 to 6. This factor is lock-stepped, therefore every CAP J-10 and Alert J-10 carries the same quantity of PL-12 missiles.

e. PL12WpnRng

PL-12 weapons range is the range of the PL-12 missile carried by the J-10. This value varies from 35 to 50 nautical miles (Jane's Air-Launched Weapons, 2009). This factor is lock-stepped between both the CAP J-10 and the Alert J-10.

f. PL12WpnPhit

PL-12 weapon probability of hit (P_{hit}) is the probability, in percent, that the PL-12 missile hits the target. This value varies from 0.0 to 1.00.

g. PL8Ammo

PL-8 weapons quantity is the number of PL-8 infra-red guided missile carried by the J-10. PL-8 weapons quantity varies from 2 to 4. This factor is lock-stepped, therefore every CAP J-10 and Alert J-10 carries the same quantity of PL-8 missiles.

h. PL8WpnRng

PL-8 weapons range is the range of the PL-8 missile carried by the J-10. This value varies from 2 to 10 nautical miles (Jane's Air-Launched Weapons, 2009). This factor is lock-stepped between both the CAP J-10 and the Alert J-10.

i. PL8WpnPhit

PL-8 weapon probability of hit (P_{hit}) is the probability that the PL-8 missile hits the target. This value varies from 0.0 to 1.00.

j. J10AlertQty

J-10 alert quantity is the maximum number of J-10 aircraft that are in alert status. The J-10 alert aircraft will randomly launch from the enemy airfield. This number varies from 1 to 20. The upper limit of 20 is chosen because modern day aircraft are rarely deployed in groups larger than 12 to 15 aircraft.

k. J10AlertSpd

J-10 alert speed is the speed, in knots, of the J-10 aircraft. J-10 alert speed varies from 250 to 800 knots (Jane's All the World's Aircraft, 2010). J-10 alert speed is converted to MANA units by dividing the speed (in knots) by ten.

l. J10AlertStlth

J-10 alert stealth is the aircraft concealment in percent. This value varies from 25 to 90. Values used are similar to that of the F/A-18 Super Hornet. These values correspond to a RCS of 0.075 to 0.01 m^2 (Grining, 2000). A conversion of $100 - (RCS \times 1000) = concealment$ is used.

C. THE EXPERIMENT

We built the MANA model in steps. The first step involved researching and manually entering all the agents, behaviors, and variables for the baseline model into the MANA simulation. MANA's well-documented and intuitive menus made this process fairly easy, but this was still the most time-consuming step.

Once all the variables were entered into the MANA simulation, the process of testing the model began. We accomplished this by running the model while adding agents and variables in steps. First; we created and tested the interactions between friendly and J-10 CAP aircraft. Second, we modeled and tested the interaction between the NUCAS strike aircraft and the target area. Third, we added the J-10 alert aircraft and coded them to randomly launch from their start position. Finally, we examined many individual model runs to ensure proper interaction among all agents.

Testing and debugging the interactions of squads was essential to ensure that the model simulated real-world operations appropriately. We accomplished this by the extensive use of two features of MANA—the control buttons, and the squad situational awareness map.

The control button functions can used to run, pause, reset, and slow down the model. In addition, a random seed value can be entered and locked in order to investigate a particular behavior. Figure 4 shows a screen capture of the control functions.

Figure 4. Screen Capture of the Various Control Buttons (From Defense Technology Agency, 2010)

We used the squad situational awareness map to troubleshoot the interactions of various squads. A wide variety of information on situational awareness for each squad can be shown, including detections, friendly squad classifications, and threat squad classifications with their associated threat level. Figure 5 shows the situational awareness map for the F-35C JSF at the beginning of the simulation. The red squares in the center of the screen have been classified as enemies, while the white squares are contacts that have been detected but are not within the range to be classified. The blue triangles are the friendly units that are in the same squad.

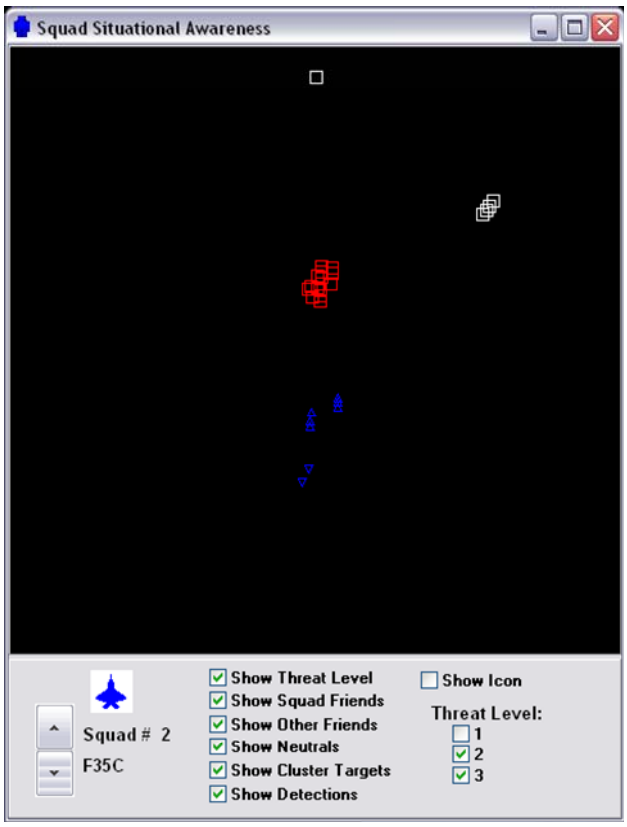

Figure 5. Screen Capture of Squad Situational Awareness Map (From Defense Technology Agency, 2010)

After completing the MANA simulation and ensuring that the model was working correctly, it was time to run the experiment. To do this, we needed an efficient experimental design. Lieutenant Colonel Thomas M. Cioppa developed a class of experimental designs called Nearly Orthogonal Latin Hypercubes (NOLHs) while earning his doctorate at NPS, Monterey, CA. The NOLH design "combines orthogonal Latin hypercubes and uniform designs to create designs having near orthogonality and excellent space-filling properties" (Cioppa and Lucas, 2007). Hernandez et al. (2009) propose variants of these designs that are even more efficient and allow a larger number of factors to be explored. In this thesis, we examine 36 different factors with some factors having a wide variety of levels between their minimum and maximum values. If this thesis were to just evaluate the eight NUCAS factors and their associated levels, the number of different combinations would reach 1.145 trillion! The value of the NOLH is that a broad section of the input space can be covered without having to produce

simulations on the entire set of input combinations. In the case of this thesis, we examine 240 different combinations by implementing the NOHL design, using the ranges of factor levels specified in Table 2 and Table 4 for the uncontrollable and controllable factors, respectively. The scatterplot matrix of Figure 6 shows the orthogonality and space-filling properties of the NOHL design used for the 24 controllable factors. The portions of the design for the uncontrollable factors (not shown) are similar. Although some factors take on a limited number of discrete levels, which tends to degrade the orthogonality, the maximum pairwise correlation between any two columns is less than 0.1.

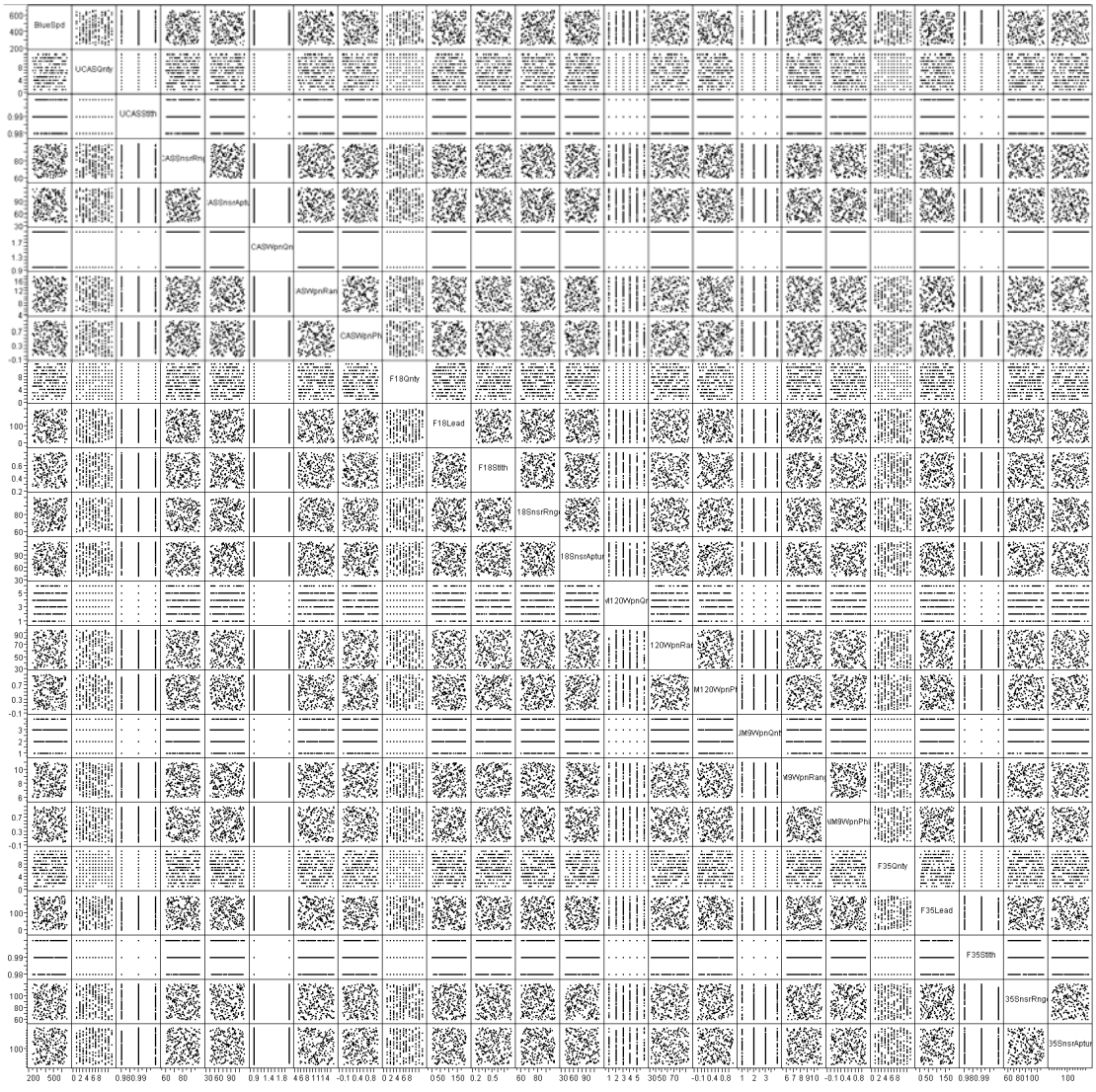

Figure 6. Scatterplot Matrix of Controllable Factors (From SAS Institute, 2010)

These 240 combinations were then entered into an executable scripting file called oldmcdata, written by my associate Steve Upton of NPS, that automatically updates the MANA XML file, produces a separate XML file for each of the 240 different combinations, and launches these on a computing cluster, in order to automate the MANA simulated runs and then collect the output data into a single comma-separated (CSV) file. These XML files are then ran on a cluster of 68 processors operated by the Simulation Experiments and Efficient Design (SEED) Center for Data Farming at NPS. 50 runs of each MANA XML file were executed making for a total of 12,000 individual simulations. On a single processor, 12,000 runs would have taken 50 hours. Using the 68-processor cluster, it took just 45 minutes, emphasizing the advantage of using NOLH experimental design in combination with the computational power of the cluster.

The entire process of creating the data file from the MANA simulation was surprisingly short, especially when compared to the extensive amount of research and development that went into creating and testing the baseline MANA simulation model.

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IV. DATA ANALYSIS

A. DATA STRUCTURE

The single CSV output file contains the following additional information:

- All controllable and uncontrollable factors with their appropriate values
- Run numbers
- Random seed numbers
- Steps required to run the simulations
- Casualty rates for every squad
- Injury rates for every squad

All analysis was performed on this CSV file exclusively using Version 8.0 of a statistical package developed by the SAS Institute called JMP (SAS Institute, 2010). As we state in Chapter I, two Measures of Effectiveness (MOEs) are of interest in this thesis: Proportion of target destruction, and proportion of friendly survivors. Generating the percentage of friendly casualties was accomplished by taking the number of friendly aircraft remaining at the end of the simulation and dividing by the number of friendly aircraft available at the start of the simulation. The blue casualty proportion was converted to blue survivability proportion by taking 1 minus the blue casualty proportion. A conversion from meters to miles was also performed in order to return the data to United States customary systems units: 1 meter is equal to 0.000621 miles.

B. INSIGHT INTO RESEARCH QUESTIONS

Chapter I lists the two research questions that directed the thesis:

- What combination of manned and unmanned aircraft provides the best mission success rate?
- What operational factors allow the NUCAS to complete its mission with limited loss rate?

A histogram of blue survivability shows that a large proportion (1180 simulations) of the 12,000 simulated runs result in zero percent blue survivability rate. The histogram with quantiles and moments is shown in Figure 7.

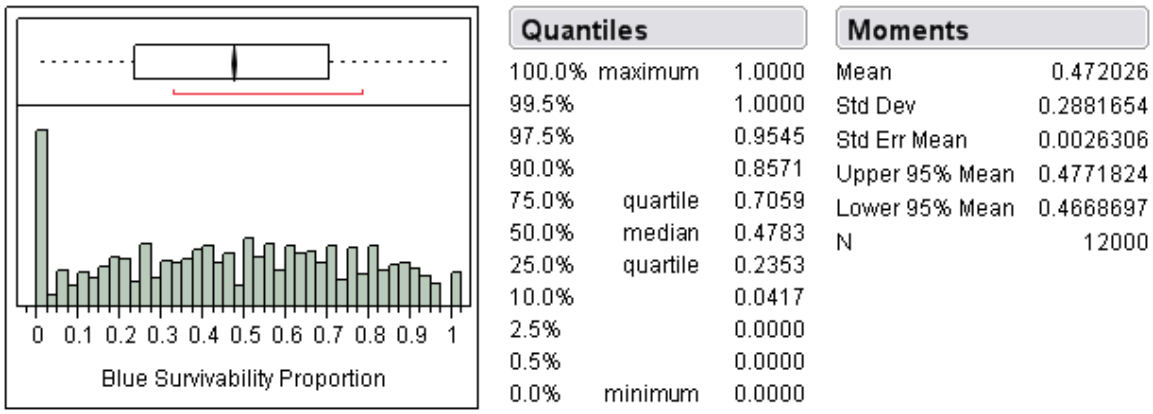


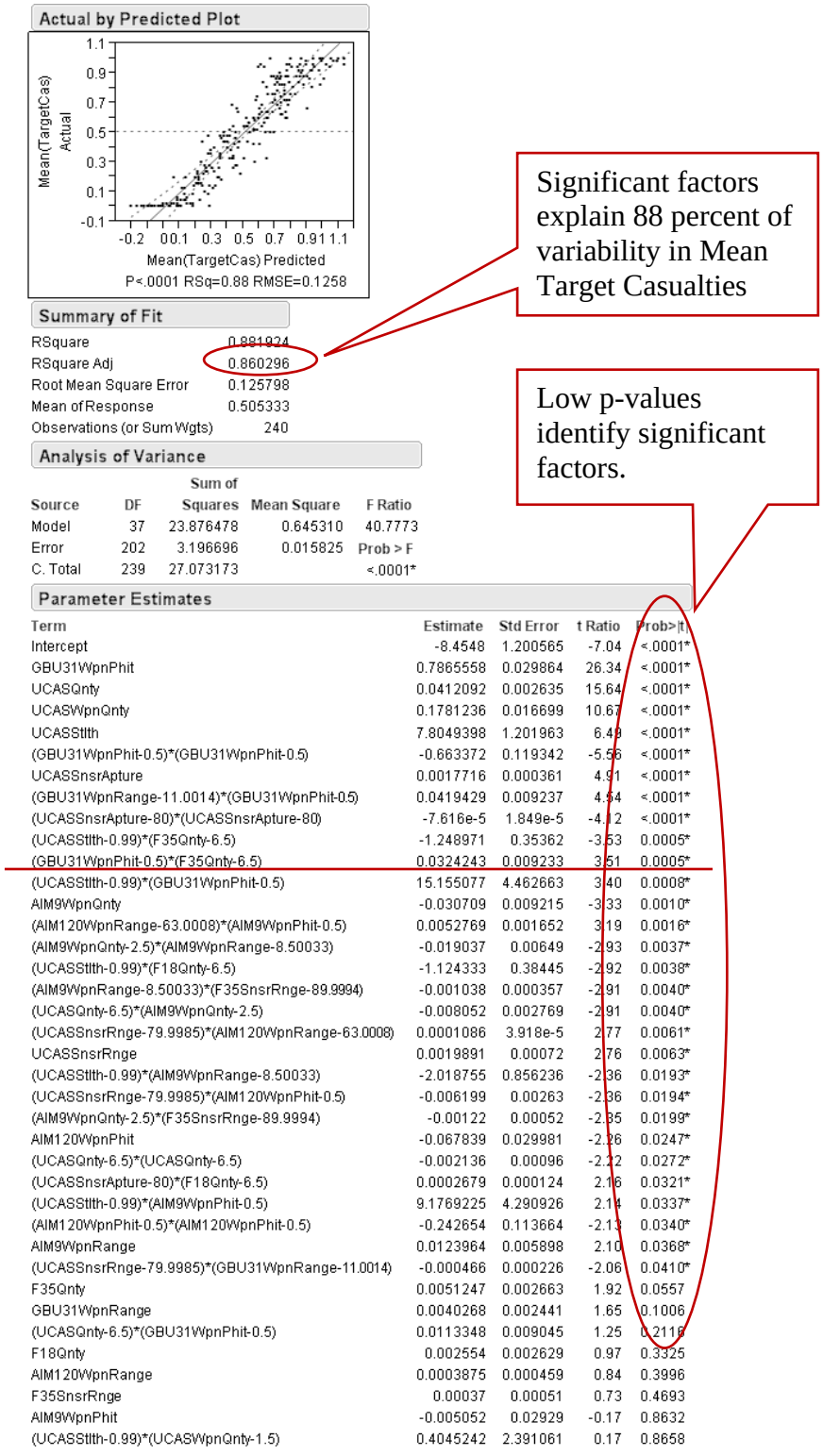
Figure 7. Histogram of Blue Survivability (From SAS Institute, 2010)

A histogram of target casualty shows the binomial characteristics of target casualty rate being either destroyed (1) or not destroyed (0). The mean of 0.505 indicates that there are slightly more destroyed targets (6064 simulations) than undestroyed targets (5936 simulations).

Throughout the rest of this chapter, the summary data file that comes from collapsing over the 50 replications for each of the different input factor combinations is referenced. This summary data file has only 240 rows of data; each row contains the input factor settings for one design point, along with the mean of each of the casualty statistics and MOEs for that design point. This summarization has some advantages for graphical displays and comparisons, and does not affect the magnitudes of any factor effect estimates in regression models or regression trees. However, the reader should note that the R Squared (R^2) for the regression models and regression trees are higher when used to predict the mean of 50 observations than when used on the raw data. Note also that some of graphs and charts in this chapter use the labels "Mean(BlueSurv%)" but these are really proportions (varying from zero to one) rather than percents (varying from zero to 100).

1. What Combination of Aircraft Provides the Best Mission Success Rate?

Mission success is a function of the target casualty proportion. We used stepwise regression to fit the mean target casualty proportion using all controllable input factors, quadratic effects, and all two-way interactions as potential terms in the model. Figure 8 shows the significant terms that explain roughly 88 percent of the variability in the mean target casualties. By convention, main effects are retained in the model for any factor appearing with significant interaction or quadratic effects.


Actual by Predicted Plot
Mean(TargetCas) Actual
Mean(TargetCas) Predicted
P<.0001 RSq=0.88 RMSE=0.1258
Significant factors explain 88 percent of variability in Mean Target Casualties
Low p-values identify significant factors.

Summary of Fit

RSquare	0.881924
RSquare Adj	0.860296
Root Mean Square Error	0.125798
Mean of Response	0.505333
Observations (or Sum Wgts)	240

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	37	23.876478	0.645310	40.7773
Error	202	3.196696	0.015825	Prob > F
C. Total	239	27.073173		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-8.4548	1.200565	-7.04	<.0001*
GBU31WpnPhit	0.7865558	0.029864	26.34	<.0001*
UCASQnty	0.0412092	0.002635	15.64	<.0001*
UCASWpnQnty	0.1781236	0.016699	10.67	<.0001*
UCASStlth	7.8049398	1.201963	6.49	<.0001*
(GBU31WpnPhit-0.5)*(GBU31WpnPhit-0.5)	-0.663372	0.119342	-5.56	<.0001*
UCASSnsrApture	0.0017716	0.000361	4.91	<.0001*
(GBU31WpnRange-11.0014)*(GBU31WpnPhit-0.5)	0.0419429	0.009237	4.54	<.0001*
(UCASSnsrApture-80)*(UCASSnsrApture-80)	-7.616e-5	1.849e-5	-4.12	<.0001*
(UCASStlth-0.99)*(F35Qnty-6.5)	-1.248971	0.35362	-3.53	0.0005*
(GBU31WpnPhit-0.5)*(F35Qnty-6.5)	0.0324243	0.009233	3.51	0.0005*
(UCASStlth-0.99)*(GBU31WpnPhit-0.5)	15.155077	4.462663	3.40	0.0008*
AIM9WpnQnty	-0.030709	0.009215	-3.33	0.0010*
(AIM120WpnRange-63.0008)*(AIM9WpnPhit-0.5)	0.0052769	0.001652	3.19	0.0016*
(AIM9WpnQnty-2.5)*(AIM9WpnRange-8.50033)	-0.019037	0.00649	-2.93	0.0037*
(UCASStlth-0.99)*(F18Qnty-6.5)	-1.124333	0.38445	-2.92	0.0038*
(AIM9WpnRange-8.50033)*(F35SnsrRnge-89.9994)	-0.001038	0.000357	-2.91	0.0040*
(UCASQnty-6.5)*(AIM9WpnQnty-2.5)	-0.008052	0.002769	-2.91	0.0040*
(UCASSnsrRnge-79.9985)*(AIM120WpnRange-63.0008)	0.0001086	3.918e-5	2.77	0.0061*
UCASSnsrRnge	0.0019891	0.00072	2.76	0.0063*
(UCASStlth-0.99)*(AIM9WpnRange-8.50033)	-2.018755	0.856236	-2.36	0.0193*
(UCASSnsrRnge-79.9985)*(AIM120WpnPhit-0.5)	-0.006199	0.00263	-2.36	0.0194*
(AIM9WpnQnty-2.5)*(F35SnsrRnge-89.9994)	-0.00122	0.00052	-2.35	0.0199*
AIM120WpnPhit	-0.067839	0.029981	-2.26	0.0247*
(UCASQnty-6.5)*(UCASQnty-6.5)	-0.002136	0.00096	-2.22	0.0272*
(UCASSnsrApture-80)*(F18Qnty-6.5)	0.0002679	0.000124	2.16	0.0321*
(UCASStlth-0.99)*(AIM9WpnPhit-0.5)	9.1769225	4.290926	2.14	0.0337*
(AIM120WpnPhit-0.5)*(AIM120WpnPhit-0.5)	-0.242654	0.113664	-2.13	0.0340*
AIM9WpnRange	0.0123964	0.005898	2.10	0.0368*
(UCASSnsrRnge-79.9985)*(GBU31WpnRange-11.0014)	-0.000466	0.000226	-2.06	0.0410*
F35Qnty	0.0051247	0.002663	1.92	0.0557
GBU31WpnRange	0.0040268	0.002441	1.65	0.1006
(UCASQnty-6.5)*(GBU31WpnPhit-0.5)	0.0113348	0.009045	1.25	0.2116
F18Qnty	0.002554	0.002629	0.97	0.3325
AIM120WpnRange	0.0003875	0.000459	0.84	0.3996
F35SnsrRnge	0.00037	0.00051	0.73	0.4693
AIM9WpnPhit	-0.005052	0.02929	-0.17	0.8632
(UCASStlth-0.99)*(UCASWpnQnty-1.5)	0.4045242	2.391061	0.17	0.8658

Figure 8. Regression Analysis of Mean Proportion of Target Casualties (After SAS Institute, 2010)

The significant factors that have the most influence are GBU-31 P_{hit}, NUCAS quantity, weapon quantity, stealth, and sensor aperture. A high R^2 value of 88 percent is obtained without considering the uncontrollable factors in the regression. This suggests that the uncontrollable factors, like enemy quantity, weapons range, and stealth, do not play as nearly an important role on mean target casualty rate as the controllable factors.

Regression tree analysis is another useful tool to determine influential factors, and it avoids problems of predictions outside of the [0,1] range for target casualty rates. Figure 9 shows a regression tree using the response variable mean target casualty and all the controllable input factors. This regression tree has five splits with an R^2 value of 0.641. This tree is read from top to bottom, with the top factors having a larger influence on the response variable. Branches on the right are preferred since the goal is to have a higher target casualty percentage. This is shown in Figure 9, by a red box indicating the poorest performing factor combinations and a green box indicating the best performing factor combinations.

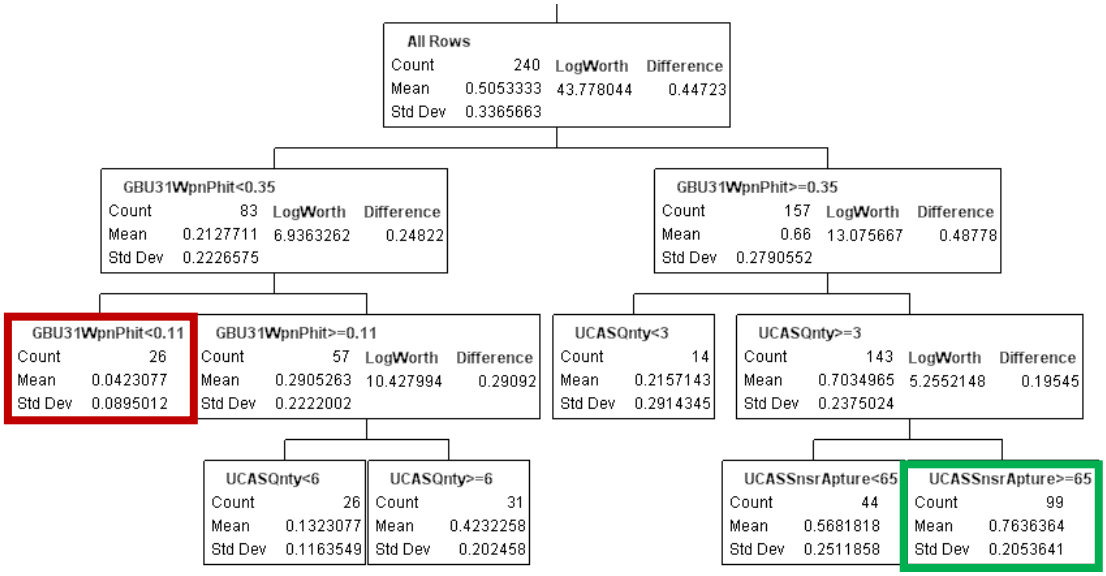


Figure 9. Regression Tree for Mean Target Casualty (After SAS Institute, 2010)

Many of the same factors that are identified as important with the stepwise regression, are also important using the regression tree: GBU-31 P_{hit}, NUCAS quantity, and sensor aperture. The regression tree also includes information about NUCAS

quantity: When the GBU-31 has a high P_{hit}, then missions involving quantities of less than three NUCAS aircraft have an average mean target casualty rate of only 0.22, while missions involving three or more NUCAS have, on average, a mean target casualty rate of 0.70. This indicates that three or more NUCAS is desirable because substantial improvements in target casualty rates can be achieved.

Graphing the mean target casualty rate versus NUCAS quantity gives further insight to using three or more NUCAS aircraft. A box plot of the mean target casualty rate versus NUCAS quantity (Figure 10) shows a very distinct difference of the slope of mean target casualty from zero to three NUCAS aircraft. The slope levels out after three, suggesting that having a larger number of NUCAS aircraft is preferred but the marginal gains are smaller beyond three NUCAS aircraft.

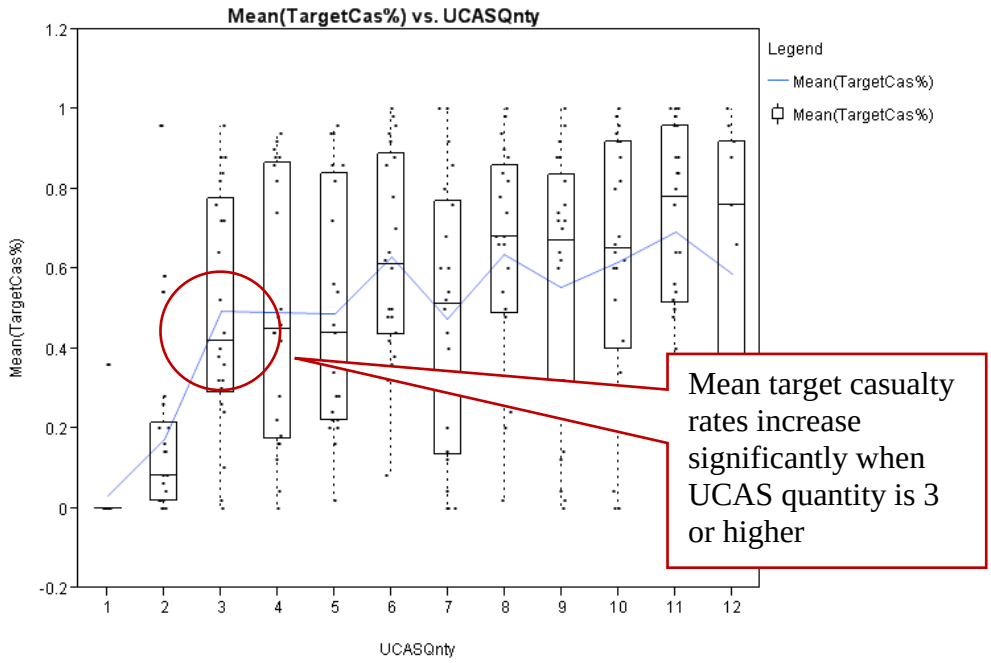


Figure 10. Box Plot of Mean Target Casualty Rate Versus NUCAS Quantity (After SAS Institute, 2010)

We evaluate NUCAS weapon quantity and stealth further by using box plots as shown in Figure 11.

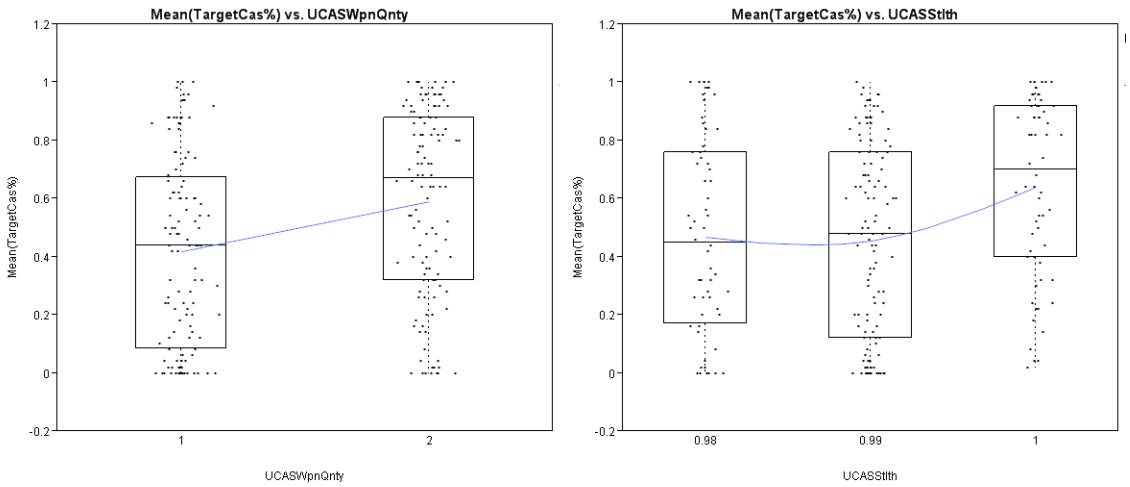


Figure 11. Box Plots of Mean Target Casualty Rate Versus NUCAS Weapons Quantity and NUCAS Stealth (From SAS Institute, 2010)

Both of the box plots of target casualty rates versus NUCAS weapons quantity and NUCAS stealth show the mean values are clearly improving as weapons quantity and stealth improve. A military significance can also be inferred, especially when improvements in mean target casualty rate increase from approximately 40 to 60 percent.

GBU-31 P_{hit} and sensor aperture are major factors determined from the regression, and deserves further exploration. Using the prediction profile option of JMP, a curve of the expected mean target casualty percentage versus each factor is shown. Figure 12 shows the prediction profile curves for both GBU-31 P_{hit} and NUCAS sensor aperture. The polynomial effects on the regression model are shown in the curvature of the mean target casualty line. The mean target casualty percentage versus GBU-31 P_{hit} displays significant gains as GBU-31 P_{hit} increases but begins to level off after GBU-31 P_{hit} of 0.8 percent. Similarly, the mean target casualty percentage versus NUCAS sensor aperture displays significant gains as the sensor aperture increases, but gains level off and then actually decrease with sensor aperture of greater than 92 degrees.

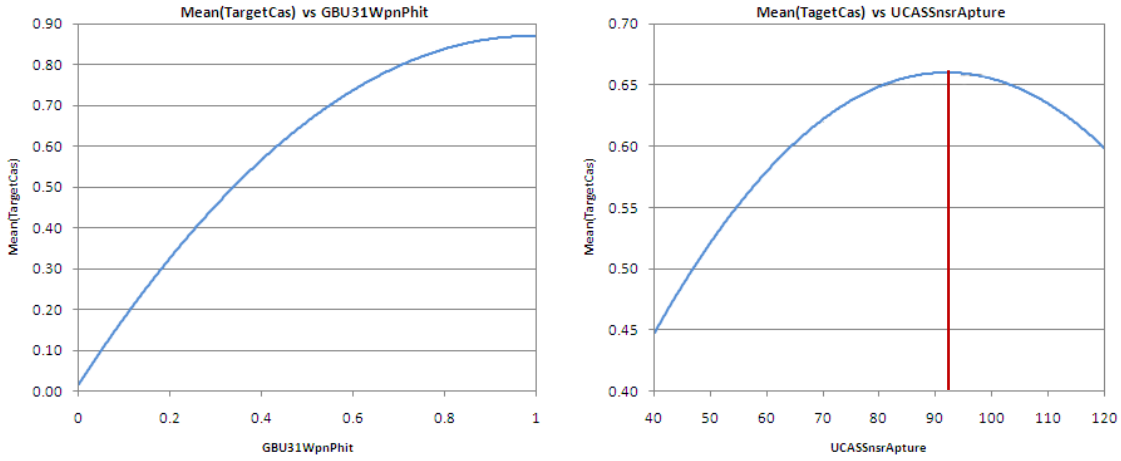


Figure 12. Side-by-Side Prediction Profile Curves of Mean Target Casualty Rate Versus GBU-31 P_{hit} and NUCAS Sensor Aperture (After SAS Institute, 2010)

In conclusion, the success of the target destruction is a direct result of the NUCAS factors. This conclusion makes sense in the simulation; the NUCAS is the only aircraft capable of destroying the ground-based target. One might expect that manned F-35C and F/A-18 quantities would also be important factors since the survivability of the NUCAS is directly related to how well the manned aircraft protect the NUCAS. However, based on the regression analysis, F-35C quantity and F/A-18 quantity are not major determinants of the target casualty rate. This may suggest that NUCAS aircraft have relative success if used autonomously, without OCA support of the F-35C or F/A-18.

2. What Factors Contribute to Minimal Blue Loss Rate?

Mission success is determined by effectively destroying the target. However, losing a majority of the aircraft directly affects the CAW's ability for further strikes. Developing tactics that ensure target destruction while minimizing blue loss rate is of vital importance if future TACAIR operations are necessary.

A stepwise regression on mean blue survivability rate was performed using all the controllable input factors, quadratic terms, and two-way interactions. Figure 13 shows the significant factors that explain roughly 60 percent of the variability in the response.

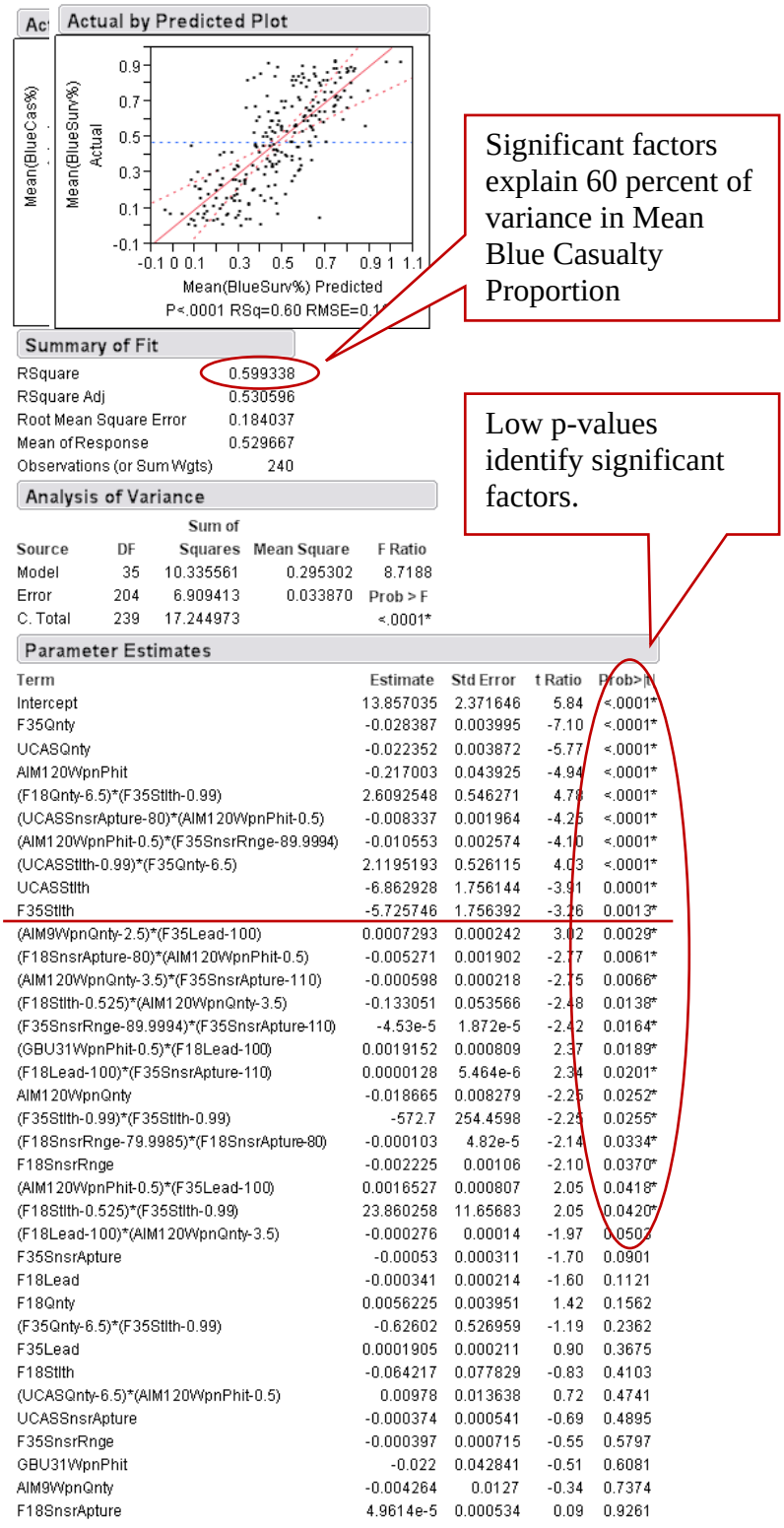


Figure 13. Regression Analysis of Mean Blue Survivability Proportion (After SAS Institute, 2010)

The significant factors that have the most influence are F-35C quantity, NUCAS quantity, AIM-120 Weapon P_{hit}, and stealth of the NUCAS and F-35C.

Figure 14 shows a regression tree of mean blue survivability using all the controllable input factors as potential explanatory factors. This regression tree has five splits with an R^2 value of 0.275. Like the previous tree, this tree is read from top to bottom, with the top factors having a larger influence on the response variable. Branches on the right tend to be preferred since the goal is to have a higher target casualty percentage. This is shown in Figure 14 by a red box indicating the poorest performing factor combinations, and a green box indicating the best performing factor combinations.

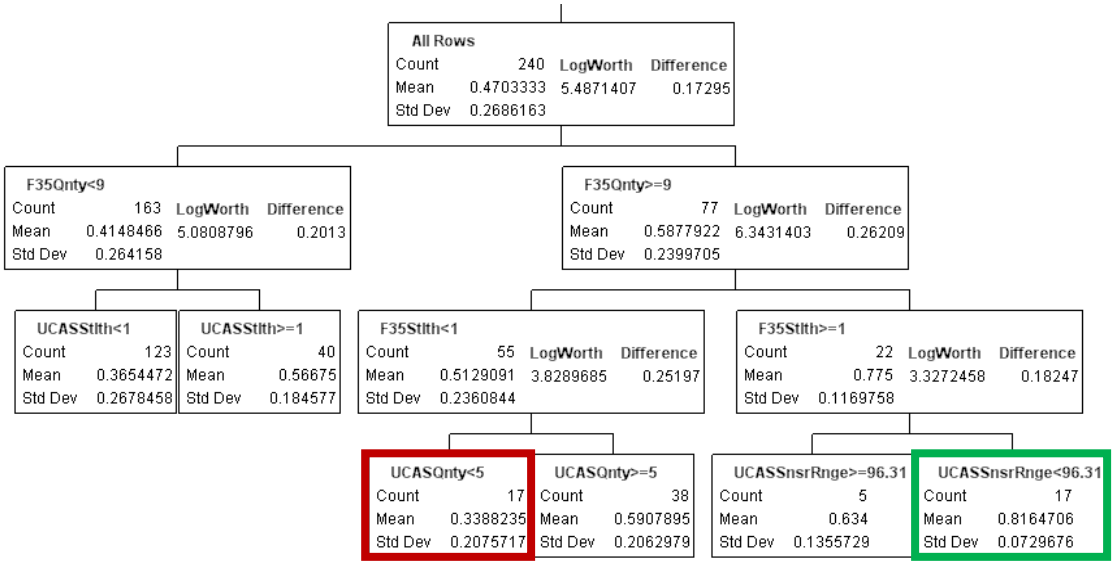


Figure 14. Regression Tree for Mean Blue Survivability Percentage (After SAS Institute, 2010)

The regression tree shows that many of the same factors that are important with the stepwise regression are also important using the regression tree: F-35C quantity, NUCAS quantity, F-35C stealth, and NUCAS stealth. Quantities of less than nine F-35C aircraft have the greatest effect on blue survivability percentage. The regression tree also highlights that, even with the small number of splits, there is a wide variation in mean

blue survivability rates, ranging from 0.33 to 0.81 (33 percent to 81 percent). This suggests that F-35C aircraft quantities greater than nine are not enough to lead to high mean blue survivability rates.

For a more detailed look at the effects of F-35C quantity on survivability, a box plot of the mean blue survivability rate versus F-35C quantity is shown in Figure 15. A similar box plot showing mean blue survivability rate versus NUCAS quantity is shown in Figure 16.

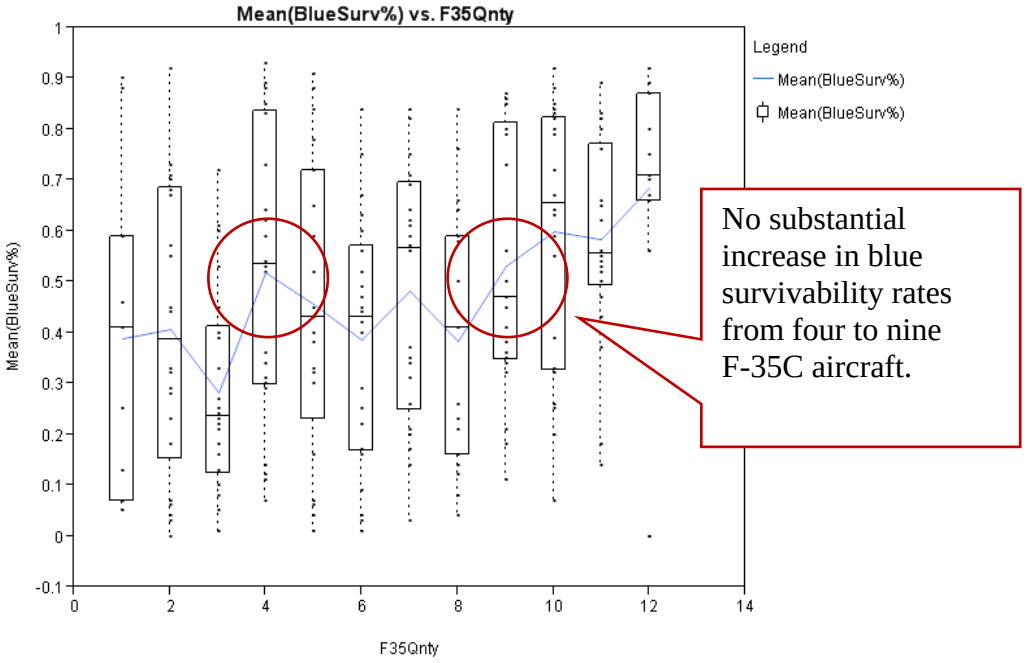


Figure 15. Box Plot of Mean Blue Survivability Percentage Versus F-35C Quantity (After SAS Institute, 2010)

It is of interest to note that when a line is drawn through the mean of each of the F-35C quantities, the curve is noticeably steeper from three to four (and again from eight to ten aircraft). This suggests, that based on the simulation data, increasing the quantity of F-35Cs aircraft from four to eight does not offer considerable advantages. However, using nine or more aircraft does improve the blue survivability percentage.

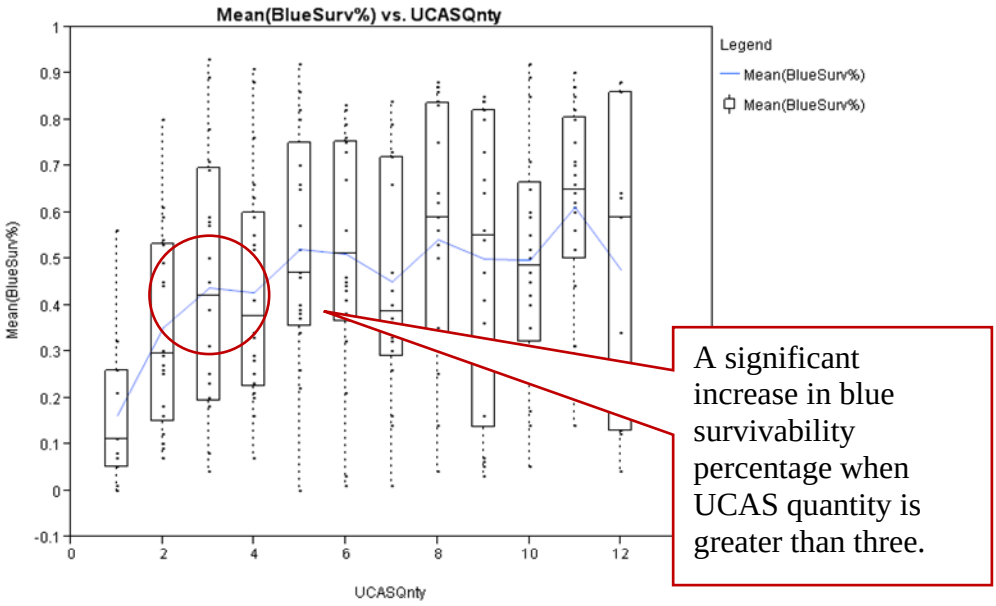


Figure 16. Box Plot of Mean Blue Survivability Percentage Versus NUCAS Quantity (After SAS Institute, 2010)

When evaluating the box plot of mean blue survivability percentage versus NUCAS quantity, a similar significant reduction in mean blue survivability percentage occurs when NUCAS quantity is greater than three aircraft. This is especially interesting since three or more NUCAS aircraft is the preferred number when mean target casualty rate is the response variable. Figure 17 is a side-by-side comparison of mean target casualty rate and mean blue survivability rate versus NUCAS quantity:

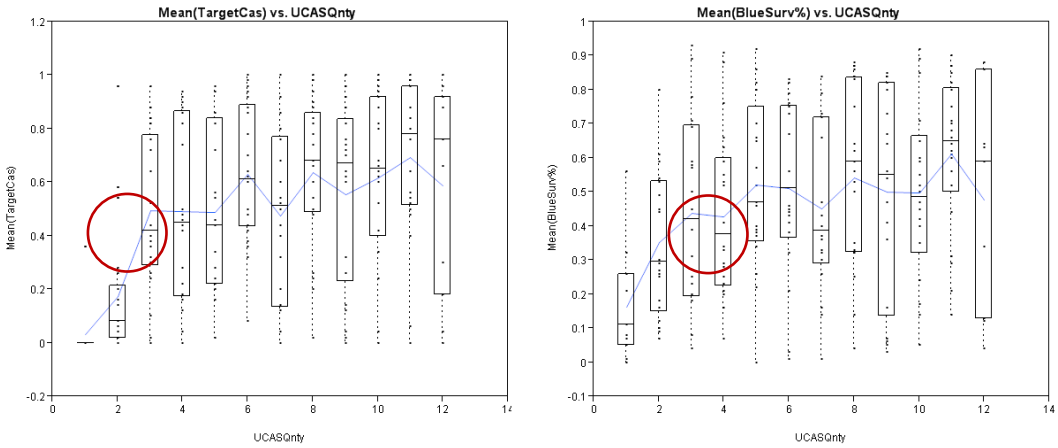


Figure 17. Side-by-Side Comparison of Mean Target Casualty Rate and Mean Blue Survivability Rate Versus NUCAS Quantity (After SAS Institute, 2010)

NUCAS and F-35 stealth are major factors determined from the regression, and deserve further exploration. Using the prediction profile option of JMP, a curve of the expected mean blue survivability percentage versus each factor is shown. Figure 18 shows the prediction profile curves for both NUCAS stealth and F-35 stealth. Both of the curves clearly show that blue survivability rate increases with stealth. Both of these graphs show the military significance of stealth in mean blue survivability. Small percentile gains of just 0.02 in stealth result in gains of at least 15 percent in mean blue survivability.

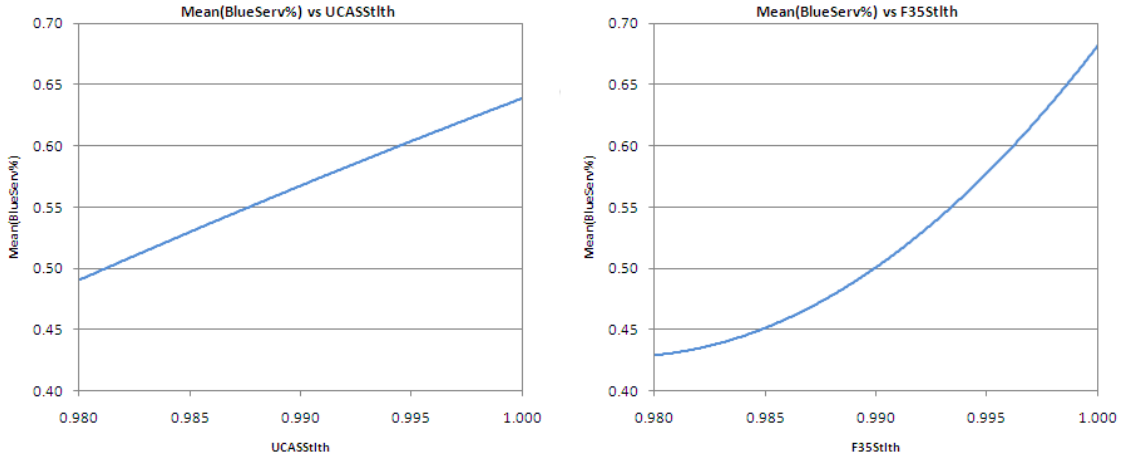


Figure 18. Prediction Profile Curves of Mean Blue Survivability Percentage Versus NUCAS Stealth and F-35C Stealth (After SAS Institute, 2010)

AIM-120 weapon P_{hit} is another major factor determined from the regression, and deserves further exploration. A prediction profile curve showing blue survivability rate versus AIM-120 Weapon P_{hit} is shown in Figure 19. This linear relationship shows a significant increase in mean blue survivability rate as AIM-120 P_{hit} increases. This highlights the importance of continued development of weapons designed to increase the P_{hit} characteristics.

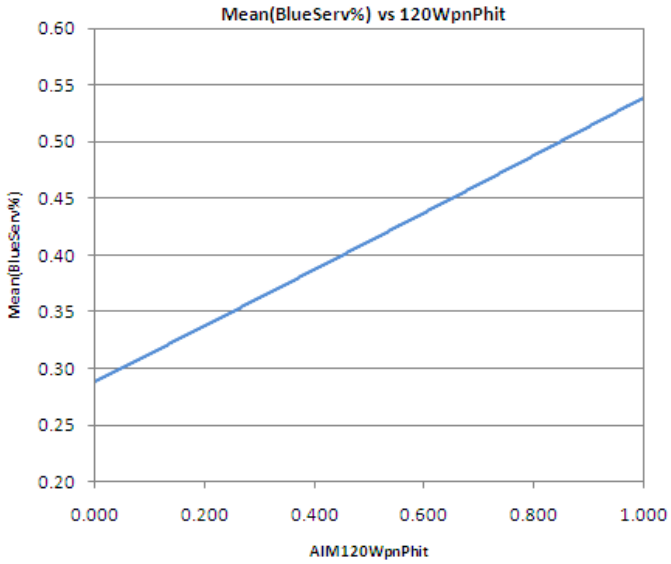


Figure 19. Prediction Profile Curve of Mean Blue Survivability Percent Versus AIM-120 Weapons P_{hit} (After SAS Institute, 2010)

In conclusion, the major factors that reduce the blue survivability percentage include F-35C quantity, NUCAS quantity, AIM-120 weapon P_{hit}, NUCAS stealth, and F-35C stealth. F-35C quantity is the most important factor; however, no substantial increase in blue survivability rates are seen when the quantity of F-35C aircraft ranged from four to nine aircraft. NUCAS quantity is the second most important factor, showing that three or more NUCAS aircraft are preferred.

V. CONCLUSIONS AND RECOMMENDATIONS

A. RESEARCH QUESTIONS

This purpose of this thesis is to gain some insight to the following questions: What combination of manned and unmanned aircraft provides the best mission success rate? What operational factors allow the NUCAS to complete its mission with limited loss rate to manned and unmanned aircraft?

1. What Combination of Aircraft Provides the Best Mission Success Rate?

When the response factor was target casualty percentage, the regression model analysis shows that NUCAS quantities of three or more produce significant gains in mission success rate. Box plot analysis shows that maximizing the NUCAS weapons quantity and stealth are militarily significant factors. Using the regression model produced from stepwise regression, the prediction profiler curves show that NUCAS sensor apertures near 92 degrees lead to improved target casualty rates. The prediction profile curves also show that improvements to GBU-31 weapon P_{hit} percentages lead to increases in target casualty rates as well.

2. What Factors Contribute to Minimal Blue Loss Rate?

When blue survivability is the response factor, regression analysis shows that a NUCAS quantity of three or more aircraft produces significant gains in blue survivability. F-35C quantities between four and nine aircraft also aid in blue survivability rates. The prediction profiler curves show that NUCAS and F-35C stealth are important factors. In addition, the prediction profile curves shows AIM-120 weapon P_{hit} is another important factor in the survivability of blue aircraft.

B. RECOMMENDATIONS

We recommended that, based on the scenario and simulation data provided:

- NUCAS aircraft should be operated in a group of at least three to four aircraft. Military aviators have a long history of working in a section of two or a division of four aircraft. Based on the reality of equipment failure, we recommended that NUCAS operate in a division of four aircraft in order maximize both probability of target destruction and blue survivability.
- F-35C aircraft should operate in a group of at least four aircraft when used for OCA missions against a large number of enemy aircraft. Marginal gains in blue survivability are achieved by increasing the quantity of F-35Cs beyond four aircraft.
- Stealth is an important factor for both successful target destruction and blue survivability. The F-35C proved to outperform the F/A-18 even when sensor and weapons parameters were equal among the two aircraft.
- Weapons P_{hit} is a major factor in target destruction and blue survivability. Weapons technology advances must continue to improve thus ensuring P_{hit} efficiency is maintained.

C. CONTINUED RESEARCH

This thesis originally included three scenarios that were to be evaluated. In addition to the coordinated strike scenario, a Defensive Counter Air (DCA) scenario and an autonomous NUCAS long-range strike were developed. Both of the scenarios were implemented into MANA with extensive testing done on both simulation models.

The DCA scenario model uses F/A-18 and F-35C manned aircraft that are positioned at a Combat Air Patrol (CAP) station. The CAP aircraft intercept and destroy inbound strike aircraft that approach randomly. The NUCAS is equipped as an in-flight refueling platform with external tanks and a central refueling pod. As F/A-18 and F-35C

aircraft require fuel, the NUCAS will intercept and rendezvous with manned aircraft to provide fuel necessary for continued airborne operations. Research questions include: How many NUCAS and DCA aircraft are needed in order to provide statistical gains in DCA effectiveness? Which factors are most important in managing DCA effectiveness? Figure 20 shows a MANA screen-shot of the DCA scenario.

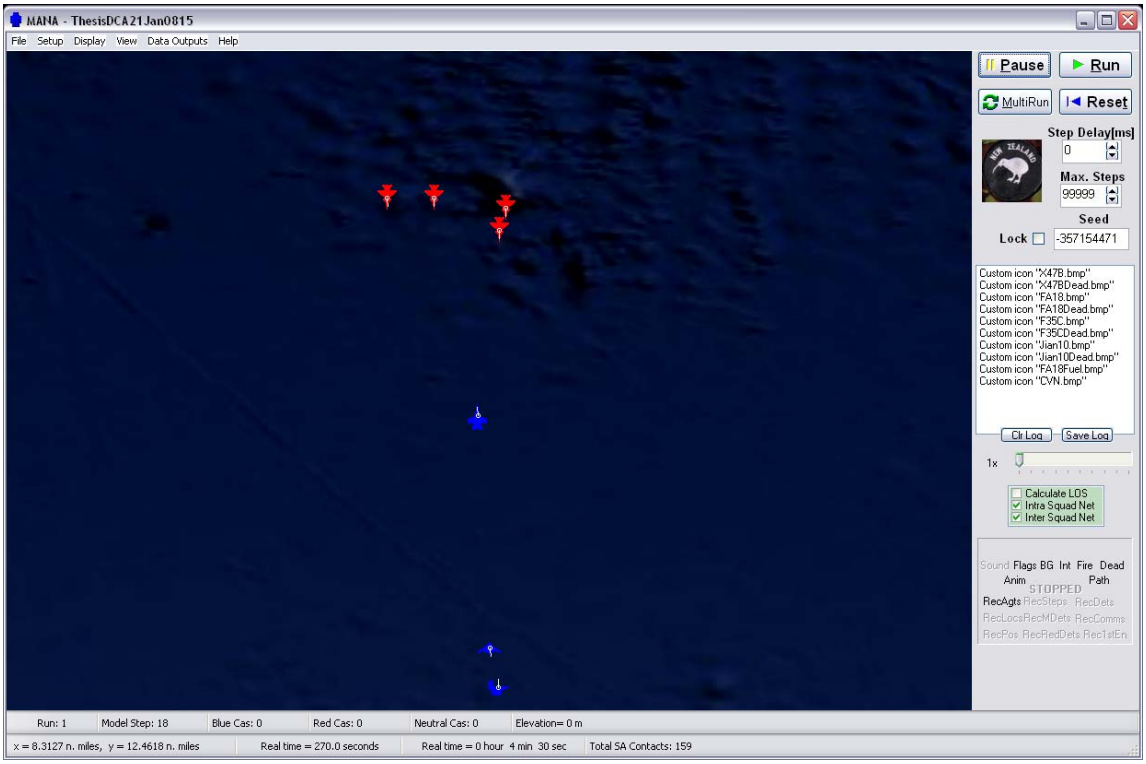


Figure 20. MANA Screen Shot of DCA Scenario (From Defense Technology Agency, 2010)

The autonomous long-range strike scenario model was developed to look strictly at the factors of the NUCAS. The scenario is a long-range strike where NUCAS aircraft are designated to destroy a target deep into enemy territory. Threats include long-range strategic and medium range tactical Surface to Air Missile (SAM) sites. The NUCAS route is predetermined to fly into the enemy territory, strike the target, and then egress while avoiding the Weapon Engagement Zones (WEZ) of the strategic SAM threats. The tactical SAM threats are randomized throughout the enemy territory. If the NUCAS successfully detects the tactical SAM threat then the UCAS will attempt to maneuver away from the WEZ. Research questions include: How many UCAS aircraft are required

to successfully destroy the target? What factors are crucial to the success of the mission? What factors are crucial to the survivability of the UCAS? Figure 21 shows a MANA screen-shot of the long-range strike scenario:

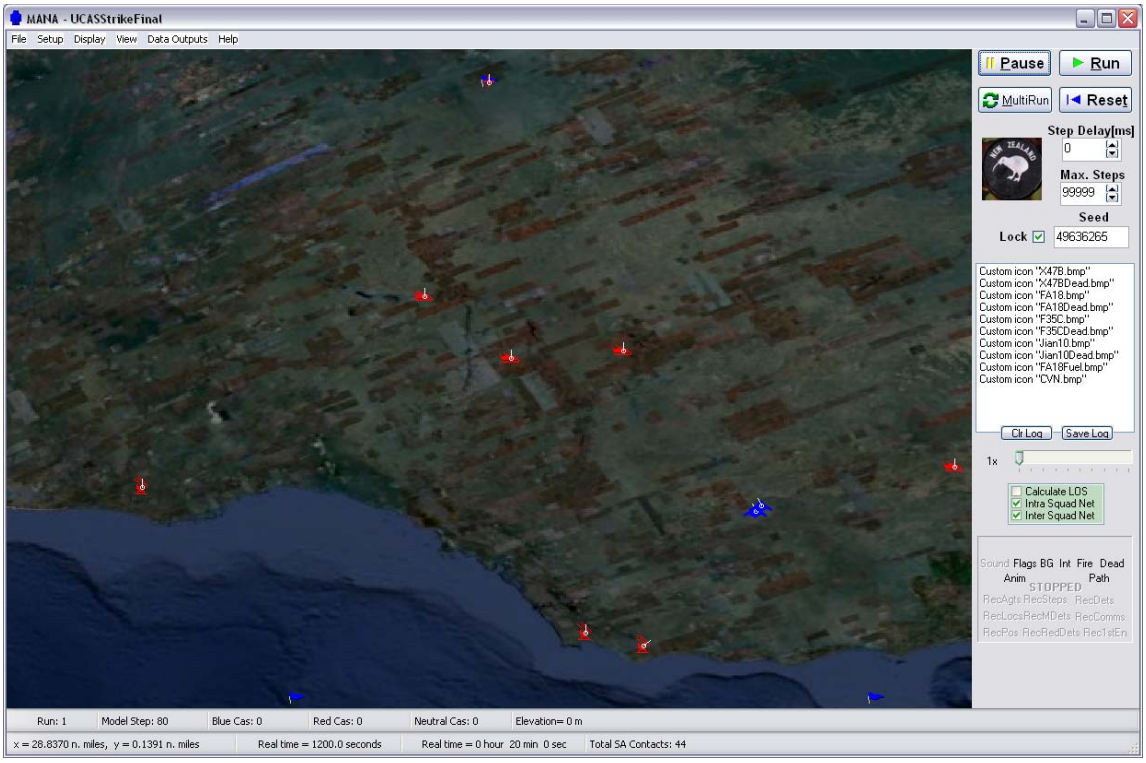


Figure 21. MANA Screen Shot of Long-Range Strike Scenario (From Defense Technology Agency, 2010)

Since much of the research and development has been done on these two scenarios, it would be advantageous to continue with the design of experiments and analysis of these two models. This information, used in combination with the coordinated strike scenario described in this thesis, would provide valuable insight into the future of NUCAS operations and CAW combat performance.

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